

UTILITY PATENT
APPLICATION TRANSMITTAL

(Only for new nonprovisional applications
under 37 CFR 1.53(b))

Attorney Docket No.

990527

Total Pages

First Named Inventor or Application Identifier

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Kazuhiko HORINO and Reiko SOEJIMA

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APPLICATION ELEMENTS FOR:
OPTICAL SEMICONDUCTOR DEVICE HAVING AN
EPITAXIAL LAYER OF III-V COMPOUND
SEMICONDUCTOR MATERIAL CONTAINING N AS A
GROUP V ELEMENT

ADDRESS TO: Assistant Commissioner for Patents
BOX PATENT APPLICATIONS
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1. [XX] Fee Transmittal Form (Incorporated within this form) (The filing fee is deferred).

2. [XX] Specification Total Pages [59]

3. [XX] Drawing(s) (35 USC 113) Total Sheets [20]

4. [] Oath or Declaration Total Pages []
Not attached; deferred under P. L. 97-247.

a. [] Newly executed (original or copy)

b. [] Copy from prior application (37 CFR 1.63(d))
(for continuation/divisional with Box 17 completed).

i. [] Deletion of Inventor(s)

Signed statement attached deleting inventor(s) named in prior application,
see 37 CFR 1.63(d)(2) and 1.33(b).

5. [] Incorporation by reference (useable if box 4b is checked)

The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under
Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby
incorporated by reference therein.

6. [] Microfiche Computer Program (Appendix)

7. [] Nucleotide and/or Amino Acid Sequence Submission (if applicable, all necessary)

a. [] Computer Readable Copy

b. [] Paper Copy (identical to computer copy)

c. [] Statement Verifying identity of above copies

ACCOMPANYING APPLICATION PARTS

8. [] Assignment Papers (cover sheet and document(s))

9. [] 37 CFR 3.73(b) Statement (when there is an assignee) [] Power of Attorney

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PAGE 2 OF 3

10. ☐ English translation Document (if applicable)

11. ☐ Information Disclosure Statement ☐ Copies of IDS Citations

12. ☐ Preliminary Amendment

13. ☒ Return Receipt Postcard (MPEP 503)

14. ☐ Small Entity Statement(s) ☐ Statement filed in prior application
Status still proper and desired.

15. ☐ Claim for Convention Priority ☐ Certified copy of Priority Document(s)

a. Priority of _____ application no. _____ filed on _____ is claimed under 35 USC 119.
The certified copies/copy have/has been filed in prior application Serial No. _____.
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16. ☐ Other _____

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FEE TRANSMITTAL	Number Filed	Number Extra	Rate	Basic Fee
The filing fee is calculated below				\$760.00
Total Claims	24 - 20	4	x \$18.00	72.00
Independent Claims	8 - 3	5	x \$78.00	390.00
Multiple Dependent Claims			\$260.00	
Basic Filing Fee				1222.00
Reduction by 1/2 for small entity				
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PAGE 3 OF 3

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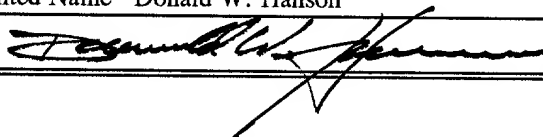
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Reg. No. 27,133

Signature



Date: May 18, 1999

DWH/yap

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, Akito Kuramata, a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan, Shinichi Kubota, a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan, Kazuhiko Horino, a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan and Reiko Soejima, a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan have invented certain new and useful improvements in

OPTICAL SEMICONDUCTOR DEVICE HAVING AN EPITAXIAL
LAYER OF III-V COMPOUND SEMICONDUCTOR MATERIAL
CONTAINING N AS A GROUP V ELEMENT

of which the following is a specification : -

1 TITLE OF THE INVENTION

 OPTICAL SEMICONDUCTOR DEVICE HAVING AN
EPITAXIAL LAYER OF III-V COMPOUND SEMICONDUCTOR
MATERIAL CONTAINING N AS A GROUP V ELEMENT

5

BACKGROUND OF THE INVENTION

 The present invention generally relates to
optical semiconductor devices and more particularly to
a GaN-family laser diode producing blue to ultraviolet
10 radiation and a fabrication process thereof.

 Laser diodes, light-emitting diodes and
photodiodes are optical semiconductor devices used
extensively in the field of optical telecommunication,
optical information processing, recording of
15 information, and the like.

 In the case of laser diode, there is a
demand, particularly in the field of optical
information recording, for a laser diode operable in
the optical wavelength band of blue to ultraviolet
20 radiation for increasing the recording density. It
should be noted a laser diode oscillates generally in
the optical wavelength band of red to infrared
radiation. Further, there is a demand for a
photodiode operable in such a short optical wavelength
25 band.

 Conventionally, GaN, having a large bandgap,
has been recognized as a promising material for
constructing an optical semiconductor device such as a
laser diode or photodiode that operates in the
30 foregoing blue to ultraviolet wavelength band. A
light-emitting diode using a GaN crystal for the
active layer thereof is already put into practical
use. Further, a laser diode having a double
heterostructure of GaN/InGaN/GaN is already known. By
35 incorporating an appropriate impurity element into the
GaN crystal, it is also possible to cause the laser
diode to oscillate in the visible wavelength band of

1 green radiation.

It should be noted that GaN has a Wurtzite structure belonging to the hexagonal crystal system, and the preparation of a single crystal substrate of GaN is difficult. Thus, the optical semiconductor devices that use GaN for the active layer have been constructed on the c-surface of a sapphire (Al_2O_3) substrate, which also belongs to the hexagonal crystal system. Thereby, the GaN active layer is grown on the foregoing c-surface of sapphire substrate epitaxially.

FIG.1 shows the construction of a conventional GaN-family laser diode 1 operable in the optical wavelength band of blue to ultraviolet radiation.

Referring to FIG.1, the laser diode 1 is formed on a sapphire substrate 11 and includes a GaN buffer layer 12 formed on the substrate 11, an n-type GaN electrode layer 13 formed on the GaN buffer layer 12, and a lower cladding layer 14 of n-type AlGa_N formed on the electrode layer with a composition of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$.

On the lower cladding layer 14, there is formed an optical waveguide layer 15 of n-type GaN, and an active layer having a multiple quantum well (MQW) structure is formed on the n-type optical waveguide layer 15 epitaxially, wherein the MQW structure includes a repetitive stacking of a unit structure of undoped InGa_N quantum well layer sandwiched by a pair of undoped GaN barrier layers.

The active layer 15 is covered by an optical waveguide layer 17 of p-type GaN, and an upper cladding layer 18 of p-type AlGa_N is formed on the optical waveguide layer 17 with a composition of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$. The upper cladding layer 18 is formed with an optical waveguide ridge 18A extending in the axial direction of the laser diode at a laterally central part thereof, and a contact layer 19 of p-type

1 GaN is formed on the top surface of the optical
waveguide ridge 18A.

The upper cladding layer 18 and the GaN
contact layer 19, including both side walls of the
5 optical waveguide ridge 18A, are covered by an
insulation film 20 of SiO_2 , and a p-side electrode 21
is formed on the insulation film 20 in electrical
contact with the GaN contact layer at the optical
waveguide ridge 18A via a via-hole formed in the
10 insulation film 20.

The foregoing semiconductor layers 14 - 18
form together a stacked layered structure defined by
two vertical side walls W_1 and W_2 extending
substantially vertically to the principal surface of
15 the substrate 11. Further, there is formed an optical
cavity in the stacked layered structure by a pair of
mirror surfaces disposed so as to face in a direction
perpendicularly to the sheet of FIG.1.

Further, the substrate 11, buffer layer 12
20 and the electrode layer 13 thereon extend laterally
beyond the foregoing side wall surface W_2 , and an n-
side electrode 22 is provided on the electrode layer
13. The laser diode of FIG.1 oscillates in the
optical wavelength of 390 - 420 nm and has an
25 important application in the field of high-density
information recording.

The laser diode of FIG.1, however, has a
drawback in that, due to the existence of large
lattice misfit of as much as 13% or more at the
30 heteroepitaxial interface between the c-surface of the
sapphire single crystal substrate 11 and the GaN
epitaxial layer 12, the epitaxial layers 15 - 17
forming the MQW structure 16 tend to include various
crystal defects with a high concentration level.
35 Further, the laser diode 1 of FIG.1 has a difficulty,
contrary to the conventional edge-emission type, in
that formation of the electrode on the bottom surface

1 of the sapphire substrate 11 is difficult. Thereby,
the construction, and hence the fabrication process of
the laser diode becomes inevitably complex. In
addition, the sapphire substrate used in the laser
5 diode 1 is difficult to be cleaved, and thus, it is
difficult in the laser diode 1 to form the mirror
surfaces by a conventional cleaving process, contrary
to the conventional edge-emission type laser diode
constructed on a substrate having a zinc blende
10 structure.

In the laser diode 1 of FIG.1, the foregoing
mirror surfaces are formed by a dry etching process,
while such a process of forming the mirror surface by
a dry etching process takes a substantial time.
15 Further, the quality of the mirror surfaces thus
formed is inferior, in terms of flatness and angle, to
the quality of the mirror surfaces formed by a
cleaving process.

It is also proposed to use a conductive SiC
20 substrate, which also belongs to the hexagonal crystal
system, in place of the sapphire substrate and form
the GaN-family active layer of the optical
semiconductor on such an SiC substrate. For example,
the Japanese Laid-Open Patent Publication 10-135576
25 describes a technology of growing a GaN-family active
layer on the (0001)Si surface of a 6H-SiC single
crystal substrate epitaxially. It should be note that
use of an SiC substrate has various advantageous
features such as small lattice misfit, less than 4%,
30 between the GaN active layer and the SiC substrate,
electrical conductivity of the substrate, and
excellent thermal conductivity of the substrate, which
is superior to that of a sapphire substrate. Thus, by
using an SiC substrate, it is possible to construct a
35 laser diode oscillating in the optical wavelength of
blue to violet radiation by using a construction
similar to that of a conventional edge-emission type

1 laser diode.

In order to construct an optical semiconductor device that uses a GaN-family active layer formed on such an SiC substrate epitaxially, it is necessary to establish a technology to form a GaN buffer layer on the SiC substrate epitaxially. Unfortunately, it is known that an epitaxial growth of a GaN layer tends to lead to an island-like growth when the growth is conducted on a SiC substrate. When such an island-like growth occurs in the buffer layer, it is difficult to form the GaN-family active layer thereon with a planarized top surface. Further, the GaN-family active layer thus formed tends to incorporate therein various crystal defects, while such crystal defects impedes the interaction occurring in the active layer between GaN and photons. Thereby, the efficiency of laser oscillation is deteriorated seriously.

It is known that the problem of island-like growth of GaN film is avoided when the SiC substrate is covered by a buffer layer of AlN or AlGaIn, such that the desired epitaxial growth of the GaN active layer occurs on such a buffer layer. However, it has been not possible to provide electrical conductivity to an AlN film used for the buffer layer.

When a buffer layer of AlGaIn is used, on the other hand, it is possible to provide an n-type conductivity to the buffer layer, as long as the content of Al in the AlGaIn buffer layer does not exceed 40%. Thus, as long as the composition of the AlGaIn layer is controlled as such, it is possible to electrically interconnect the GaN active layer with the SiC substrate via the AlGaIn buffer layer.

On the other hand, the condition of forming the conductive AlGaIn epitaxial film on a SiC substrate with a flat and smooth top surface suitable for forming an active layer of GaN thereon, has not been

1 explored to the date.

SUMMARY OF THE INVENTION

5 Accordingly, it is an object of the present invention to provide a novel and useful optical semiconductor device and a fabrication process thereof wherein the foregoing problems are successfully eliminated.

10 Another and more specific object of the present invention is to provide an optical semiconductor device having an SiC substrate and a nitride layer of a group III element including Ga formed epitaxially on the substrate, wherein the epitaxial layer has a flat and smooth top surface and
15 that an excellent electrical interconnection is secured between the SiC substrate and the nitride epitaxial layer.

20 Another object of the present invention is to provide an optical semiconductor device having a simple structure for confining the electric currents injected to the laser diode into a desired stripe region and is simultaneously capable of controlling the transverse mode oscillation in the state that laser diode produces a high-power optical output.

25 Another object of the present invention is to provide an optical semiconductor device having a selectively grown region of nitride and a fabrication process thereof.

30 Another object of the present invention is to provide an optical semiconductor device having a nitride active layer of a group III element including Ga and an electron blocking layer provided for preventing overflowing of electrons from the active layer, wherein the doping of the electron blocking
35 layer is optimized such that crack formation is minimized, the carrier confinement in the active layer is maximized and the threshold voltage of laser

1 oscillation is minimized.

Another object of the present invention is to provide an optical semiconductor device, comprising:

5 a substrate of SiC having a first conductivity type;

 a buffer layer of AlGa_N formed on said substrate epitaxially, said buffer layer having said first conductivity type and a composition represented
10 as $\text{Al}_x\text{Ga}_{1-x}\text{N}$;

 a first cladding layer having said first conductivity type, said first cladding layer being formed on said buffer layer epitaxially;

 an active layer formed epitaxially on said
15 first cladding layer;

 a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

 a first electrode provided so as to inject
20 first-type carriers having a first polarity into said second cladding layer; and

 a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,

25 said buffer layer containing said first type carriers with a concentration level from $3 \times 10^{18}\text{cm}^{-3}$ to $1 \times 10^{20}\text{cm}^{-3}$ and said compositional parameter x larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

 According to the present invention, the
30 resistance at the interface between the substrate and the buffer layer is effectively minimized.

Another object of the present invention is to provide an optical semiconductor device, comprising:

35 a substrate of SiC having a first conductivity type;

 a buffer layer of AlGa_N formed on said

1 substrate epitaxially;
a first cladding layer of AlGa_N having said
first conductivity type, said first cladding layer
being formed on said buffer layer epitaxially;
5 an optical waveguide layer of Ga_N having
said first conductivity type, said optical waveguide
layer being formed on said first cladding layer
epitaxially;
an active layer formed epitaxially on said
10 optical waveguide layer, said active layer containing
Ga as a group III element and N as a group V element;
a second cladding layer of AlGa_N having a
second, opposite conductivity type, said second
cladding layer being formed on said active layer
15 epitaxially;
a first electrode provided so as to inject
first-type carriers having a first polarity into said
second cladding layer; and
a second electrode provided on said
20 substrate so as to inject second-type carriers having
a second polarity,
said substrate having a top surface
separated from a bottom surface of said active layer
by a distance of about 1.6 μm or more.
25 According to the present invention, the
threshold current of the optical semiconductor device
is successfully minimized.
Another object of the present invention is
to provide an optical semiconductor device,
30 comprising:
a substrate of SiC having a first
conductivity type;
a first cladding layer having a first
conductivity type, said first cladding layer being
35 formed on said substrate epitaxially;
an active layer formed epitaxially on said
first cladding layer;

- 1 a second cladding layer having a second,
opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;
- a third cladding layer having said second
5 conductivity type, said third cladding layer being
formed on said second cladding layer epitaxially;
- a first electrode provided so as to inject
first-type carriers having a first polarity into said
second cladding layer; and
- 10 a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,
- said third cladding layer having a ridge
structure,
- 15 wherein an insulating film is interposed
between said second cladding layer and said third
cladding layer, said insulating film having an opening
in correspondence to said ridge structure, with a
width smaller than a width of said ridge structure.
- 20 According to the present invention, the
injection of the drive current is made into an
narrowly confined region of the ridge structure, and
an efficient control is made on the laser oscillation
of the horizontal transverse mode. As a result, the
- 25 optical semiconductor device shows a smooth
operational characteristic free from kink from a low-
power state producing a low-power optical beam to a
high-power state producing a high-power optical beam.
- Another object of the present invention is
- 30 to provide an optical semiconductor device,
comprising:
- a substrate of SiC having a first
conductivity type;
- a first cladding layer having a first
35 conductivity type, said first cladding layer being
formed on said substrate epitaxially;
- an active layer formed epitaxially on said

- 1 first cladding layer;
a second cladding layer having a second,
opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;
- 5 a third cladding layer having said second
conductivity type, said third cladding layer being
formed on said second cladding layer epitaxially;
a contact layer of said second conductivity
type, said contact layer being formed on said third
10 cladding layer;
a first electrode provided on said contact
layer;
a second electrode provided on said
substrate;
- 15 said third cladding layer forming a ridge
structure having a T-shaped cross-section,
said third cladding layer including, at a
bottom part thereof, a pair of cuts, such that said
cuts penetrate from respective lateral sides of said
20 ridge structure toward a center of said ridge
structure.
- According to the present invention, the area
of the insulation mask used in corresponding to the
foregoing cuts when forming the third cladding layer
25 by a selective growth process is effectively
minimized, and the formation of particles on the
insulation film is minimized accordingly. As the
insulation mask itself is removed after the selective
growth process and before the step of forming the
30 first electrode, the problem of deterioration of
adhesion caused in the first electrode as a result of
the existence of the particles is successfully
eliminated. As the third cladding layer thus formed
has a T-shaped cross-section characterized by a
35 narrowly confined bottom part, the optical
semiconductor device of the present invention is
capable of injecting drive current selectively into

1 an electron blocking layer of a nitride of a
group III element formed epitaxially on said active
layer, said electron blocking layer having a p-type
conductivity;

5 a second optical waveguide layer of a
nitride of a group III element formed epitaxially on
said electron blocking layer, said second optical
waveguide layer having a p-type conductivity;

10 a second cladding layer of a nitride of a
group III element formed epitaxially on said second
optical waveguide layer, said second cladding layer
having a p-type conductivity;

15 a contact layer of a nitride of a group III
element formed epitaxially on said second cladding
layer, said contact layer having a p-type
conductivity;

 a first electrode provided on said contact
layer; and

20 a second electrode provided on said
substrate;

 each of said electron blocking layer, said
second optical waveguide layer and said second
cladding layer being doped by Mg;

25 wherein said second optical waveguide layer
and said second cladding layer contain Mg therein with
a concentration level lower than a concentration level
of Mg in any of said electron blocking layer and said
contact layer.

30 According to the present invention, the
problem of cracking of the epitaxial layers in the
optical semiconductor device is minimized. Further,
the drive voltage of the optical semiconductor device
is also minimized.

35 Another object of the present invention is
to provide a semiconductor wafer, comprising:

 an SiC substrate having an n-type
conductivity; and

1 an AlGa_N layer having an n-type conductivity
formed on said SiC substrate with a composition
represented as Al_xGa_{1-x}N,
 wherein said AlGa_N layer has a carrier
5 density in the range between 3×10^{18} - 1×10^{20} cm⁻³,
and
 wherein said compositional parameter x is
larger than 0 but smaller than 0.4 ($0 < x < 0.4$).
 According to the present invention, the
10 resistance at the interface between the SiC substrate
and the AlGa_N buffer layer is minimized.
 Other objects and further features of the
present invention will become apparent from the
following detailed description when read in
15 conjunction with the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG.1 is a diagram showing the construction
of a conventional GaN-family laser diode;
20 FIGS.2A and 2B are diagrams showing the
experiments constituting one of the basis of the
present invention;
 FIG.3 is another diagram showing the
experiments constituting one of the basis of the
25 present invention;

 FIG.4 is another diagram showing the
experiments constituting one of the basis of the
present invention;
30 FIG.5 is another diagram showing the
experiments constituting one of the basis of the
present invention;
 FIGS.6A and 6B are diagrams showing the
construction of a laser diode according to a first
35 embodiment of the present invention;
 FIG.7 is a diagram showing the experiments
constituting one of the basis of the present

1

FIG.8 is a diagram showing the construction of a laser diode according to a second embodiment of the present invention;

5

FIGS.10A and 10B are diagrams showing the fabrication process of a laser diode according to a third embodiment of the present invention;

10

FIGS.12A and 12B are diagrams showing the construction of a mask used in a selective growth process when fabricating the laser diode of the third embodiment and a laser diode of a fourth embodiment of the present invention;

19

FIG.13 is a diagram showing the construction of a laser diode according to the fourth embodiment of the present invention;

20

FIG.15 is a diagram showing a distribution of Mg in a conventional laser diode;

25

FIG.17 is a diagram showing the experiments constituting one of the basis of the present invention:

30

FIG.18 is a diagram showing a Mg distribution used in a laser diode according to a sixth embodiment of the present invention;

FIG.19 is a diagram showing a Mg distribution according to a modification of the sixth embodiment.

1 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT
 [FIRST EMBODIMENT]

 In the description hereinafter, the mixed
crystal having the composition $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($0 < x < 0.4$)
5 will be designated merely as AlGaN. When the AlGaN
mixed crystal has a composition falling in the
foregoing range ($0 < x < 0.4$), the doping of AlGaN is
possible. Further, the AlGaN mixed crystal having
such a composition can be grown on an SiC substrate
10 with a flat and smooth top surface. The epitaxial
growth of the AlGaN mixed crystal is typically
conducted by an MOVPE process, wherein the epitaxial
layer thus formed shows a flat and smooth top surface
when the deposition is made under a pressure of 100
15 Torr and the AlGaN mixed crystal contains Al with an
atomic fraction x of 0.09 or more.

 Thus, it is possible to construct a GaN-
family laser diode on an n-type SiC substrate covered
by an n-type $\text{Al}_x\text{Ga}_{1-x}\text{N}$ buffer layer, by depositing
20 desired epitaxial layers of GaN or a mixed crystal of
GaN. The laser diode thus formed typically oscillates
at the wavelength of 420 nm and has a threshold
current of about 500 mA. While the laser diode thus
formed oscillates at the desired blue to ultraviolet
25 wavelength band as is expected, the laser diode also
has a drawback in that the threshold voltage necessary
for laser oscillation is very large, as large as about
22V. In view of the built-in potential of about 3V
for the pn junction in a GaN crystal, the threshold
30 voltage of the laser diode should be about 4 - 5 V if
the laser diode is fabricated properly. Thus, the
foregoing threshold voltage of 22V is deemed
excessively large for a GaN-family laser diode.

 The inventor of the present invention has
35 conducted a series of experiments on the AlGaN/SiC
epitaxial system in the investigation forming the
basis of the present invention, and discovered that

1 the foregoing large threshold voltage arises as a
result of large AlGa_N/SiC interface resistance between
the SiC substrate and the AlGa_N buffer layer.

5 In view of the fact that the band structure
of SiC and AlGa_N is not yet established to the date,
and further in view of the expected existence of
concentration of crystal defects at the interface
between the SiC substrate and the AlGa_N buffer layer,
the theoretical approach for reducing the AlGa_N/SiC
10 interface resistance is expected to be difficult.
Thus, the present invention explored the solution for
reducing the AlGa_N/SiC interface resistance
experimentally.

FIG.2A shows the construction of the sample
15 used in the experiment.

Referring to FIG.2A, a bulk crystal ingot of
Wurtzite-type 6H-SiC, doped by N to the n-type and
grown by an improved Rayleigh process, was used for
forming an SiC substrate 1. More specifically, the
20 SiC substrate 1 was formed from the foregoing 6H-SiC
bulk crystal ingot to have a thickness of about 200
μm, wherein the substrate 1 thus formed was defined by
a principal surface of (0001)Si having a surface area
of about 1 cm². The foregoing (0001)Si principal
25 surface of the substrate 1 was then covered by a
buffer layer 2 of n-type AlGa_N grown thereon
epitaxially by an MOVPE process with a thickness of
about 1 μm. The AlGa_N buffer layer 2 thus formed was
doped by Si to the n-type. The MOVPE process for
30 forming the buffer layer 2 was conducted at the
substrate temperature of 1090°C while using the
gaseous sources of TMG (trimethylgallium), TEG
(triethylgallium), TMA (trimethylaluminum) and ammonia
(NH₃) together with an impurity gaseous source of
35 monosilane (SiH₄).

After the formation of the buffer layer 2, a
contact layer 3 of n-type Ga_N was grown further on the

1 buffer layer 2 by an MOVPE process with a thickness of
about 0.2 μm for reducing the contact resistance.

After the formation of the contact layer 3,
a circular or stripe-shaped electrode 6 was formed on
5 the GaN contact layer for measurement of the AlGaIn/SiC
interface resistance, more specifically the
resistivity, between the substrate 1 and the buffer
layer 2, and a Ni electrode 5 was provided on the
bottom principal surface of the substrate 1 so as to
10 cover the entirety thereof. It should be noted that
the electrode 6 has a stacked structure including a
lower layer of Ti and an upper layer of Al, wherein
the electrode 6 was formed to have a diameter of 30 -
90 μm when the electrode 6 has a circular shape. When
15 the electrode 6 has a stripe structure, the electrode
6 was formed of a stripe having a width of 2 - 15 μm
and a length of 300 - 900 μm .

In the experiment, the carrier density was
changed variously in the n-type AlGaIn buffer layer 2
20 and also in the n-type SiC substrate, in combination
with the Al content in the buffer layer 2 and the
pressure used in the MOVPE process.

FIG.2B shows the interface resistivity at
the interface between the n-type SiC substrate 1 and
25 the n-type AlGaIn buffer layer 2 for the case the
carrier density was changed, wherein the horizontal
axis of FIG.2B represents the n-type carrier density
(cm^{-3}) in the AlGaIn buffer layer 2 in a logarithmic
scale, while the vertical axis of FIG.2B represents
30 the AlGaIn/SiC interface resistivity (Ωcm^2) also in a
logarithmic scale. In the experiment of FIG.2B, the
carrier density in the SiC substrate 1 was set to $1 \times 10^{17} \text{cm}^{-3}$
and the Al content x of the AlGaIn buffer
layer 2 was set to 0.09 (x = 0.09).

35 Referring to FIG.2B, there are represented
the value of the AlGaIn/SiC interface resistivity for
the structure of FIG.2A in which the carrier density

1 in the n-type AlGaIn buffer layer 2 is changed from $1 \times 10^{17} \text{cm}^{-3}$ to $1 \times 10^{20} \text{cm}^{-3}$. In the construction of
FIG.2A, it should be noted that the bulk resistance is
negligible for the electrodes 5 and 6, the SiC
5 substrate 1, the AlGaIn buffer layer 2 and the GaN
contact layer 3. Further, the contact resistance of
the electrode, more specifically the interface
resistance at the interface between the AlGaIn buffer
layer 2 and the contact layer 3, is also negligible.
10 Thus, the resistance measured across the electrodes 5
and 6 fairly represents the AlGaIn/SiC interface
resistance between the SiC substrate 1 and the AlGaIn
buffer layer 2.

As will be apparent from FIG.2B, the plot of
15 the resistivity reveals the existence of two lines r_1
and r_2 . More specifically, the experimental points
are aligned on a line r_2 having a gentle gradient in
the range of the carrier density larger than about $5 \times$
 10^{18}cm^{-3} , while the experimental points are aligned on
20 a more steeper line r_1 when the carrier density is
lower than the foregoing value of about $5 \times 10^{18} \text{cm}^{-3}$.

It should be noted that the gentle gradient
of the line r_2 indicates that the change of the
AlGaIn/SiC interface resistivity is small when the
25 carrier density is changed. The existence of the two
lines, r_1 and r_2 , suggests that the physical
phenomenon occurring in the range of the line r_1 may
be different from the physical phenomenon occurring in
the range of the line r_2 . From FIG.2B, it will be
30 understood that a low interface resistivity is
realized with reliability, by setting the carrier
density in the n-type AlGaIn buffer layer 2 to be
larger than about $5 \times 10^{18} \text{cm}^{-3}$.

In a GaN-family laser diode having a mesa
35 structure, the entire resistance of the epitaxial
layers generally takes the value of about 10Ω .
Thereby, it is desired and necessary that the

1 AlGaN/SiC interface resistance is substantially lower
than the total resistance of the epitaxial layers.

In the event each epitaxial layer has a size
of 700 μm x 4 μm , the AlGaN/SiC interface resistance
5 can be positively reduced to be smaller than the
resistance of the entire epitaxial layers, even when
the carrier density in the epitaxial layers is in the
order of $3 \times 10^{18} \text{cm}^{-3}$. Thus, it is preferable to dope
the n-type AlGaN layer 2 to have a carrier density of
10 about $3 \times 10^{18} \text{cm}^{-3}$ or more, more preferable about $5 \times$
 10^{18}cm^{-3} or more.

In doping the n-type AlGaN buffer layer 2,
it was discovered that there appears a large amount of
crystal defects on the surface of the AlGaN layer 2
15 when the carrier density in the layer 2 is set larger
than the value of $1 \times 10^{20} \text{cm}^{-3}$. Due to the excessive
formation of the crystal defects, experiment for
measuring the interface resistivity was not possible
in this case. Thus, it is preferable that the carrier
20 density in the n-type AlGaN buffer layer 2 does not
exceed the foregoing value of about $1 \times 10^{20} \text{cm}^{-3}$.

In the foregoing experiments, the carrier
density of the n-type AlGaN buffer layer 2 on the n-
type SiC substrate 1 was changed variously, while in
25 the second-series experiments that follow the
foregoing first-series experiments, the AlGaN/SiC
interface resistivity was measured while changing the
carrier density in the n-type SiC substrate 1
variously. In the second-series experiments, the
30 composition of the n-type AlGaN buffer layer 2 was set
to have an Al content x of 0.09 (x = 0.09) and the
carrier density of $5 \times 10^{18} \text{cm}^{-3}$.

FIG.3 shows the result of measurement of the
AlGaN/SiC interface resistivity for various carrier
35 densities in the n-type SiC substrate 1 in the range
from $1 \times 10^{17} \text{cm}^{-3}$ to $3 \times 10^{19} \text{cm}^{-3}$, wherein the
horizontal axis shows the carrier density (cm^{-3})

1 represented in a logarithmic scale, while the vertical
axis represents the AlGa_N/SiC interface resistivity
(Ωcm) in a logarithmic scale.

5 As can be seen clearly from FIG.3, the
experimental points are aligned on two lines r_3 and
 r_4 . More specifically, the AlGa_N/SiC interface
resistivity is represented by the line r_3 in the range
of the carrier density smaller than about $1 \times 10^{18}\text{cm}^{-3}$.
10 In the range of the carrier density larger than
about $1 \times 10^{18}\text{cm}^{-3}$, on the other hand, the AlGa_N/SiC
interface resistivity is represented by the line r_4 .

In the second-series experiments, it was
discovered that the quality of the SiC bulk crystal is
deteriorated substantially when the carrier density
15 therein is increased beyond the value of $1 \times 10^{20}\text{cm}^{-3}$.
Because of the poor quality of the SiC substrate 1,
the experiment was not possible in the range of the
carrier density exceeding the foregoing value of $1 \times$
 10^{18}cm^{-3} .

20 Summarizing above, it is concluded that the
n-type SiC substrate 1 preferably has the carrier
density in the range between about $1 \times 10^{18}\text{cm}^{-3}$ and 1
 $\times 10^{20}\text{cm}^{-3}$. When the carrier density is reduced below
the foregoing value of $1 \times 10^{18}\text{cm}^{-3}$, the AlGa_N/SiC
25 interface resistance increases sharply. When the
carrier density exceeds the value of $1 \times 10^{18}\text{cm}^{-3}$, on
the other hand, the quality of the SiC substrate 1 is
deteriorated.

Next, in the third-series experiment, an
30 investigation was made on the effect of the Al content
 x in the n-type AlGa_N buffer layer 2 on the AlGa_N/SiC
interface resistance. In the third-series experiment,
the carrier density in the n-type SiC substrate 1 was
set to about $1 \times 10^{18}\text{cm}^{-3}$ and the carrier density in
35 the n-type AlGa_N buffer layer 2 was set to about $5 \times$
 10^{18}cm^{-3} .

FIG.4 shows the AlGa_N/SiC interface

1 resistance of the n-type AlGa_N buffer layer 2 for the
case in which the Al content x of the buffer layer 2,
represented as Al _{x} Ga_{1- x} N, is changed variously,
wherein the horizontal axis represents the
5 compositional parameter x in terms of atomic percent,
while the vertical axis represents the AlGa_N/SiC
interface resistivity.

As can be seen from FIG.4, the experimental
points are aligned on two lines, r_5 and r_6 , wherein
10 the AlGa_N/SiC interface resistivity is represented by
the line r_5 having a gentle gradient when the
compositional parameter x is smaller than about 9%.
When the compositional parameter x increased beyond
the value of about 9%, on the other hand, the
15 interface resistivity is represented by the line r_6
having a steeper gradient. Further, the interface
resistivity increases with the compositional parameter
 x representing the Al content in the AlGa_N buffer
layer 2 in any of the lines r_5 and r_6 . Thus, from the
20 result of FIG.4, it is preferable that the Al content
 x in the n-type AlGa_N buffer layer 2 is set smaller
than 9%.

In the foregoing first through third series
experiments, the formation of the n-type AlGa_N buffer
25 layer 2 was conducted by an MOVPE process. On the
other hand, it is believed that a similar result would
be obtained also when the buffer layer 2 is formed by
other deposition process such MBE (molecular beam
epitaxy), as the value of the interface resistivity is
30 primarily controlled by the band structure and the
impurity concentration level.

Conventionally, the epitaxial growth of a
Ga_N layer or a mixed crystal layer of Ga_N has been
conducted by setting the pressure to about 100 Torr
35 when the growth is made by MOVPE. In the foregoing
experiments, the inventor of the present invention has
discovered that it is necessary to increase the Al

1 content x in the n-type AlGa_N buffer layer 2, which is
grown directly on the SiC substrate 1, to be larger
than 8% in order to obtain a flat and smooth top
surface. Further, the inventor of the present
5 invention has discovered that a flat and smooth top
surface can be obtained for the n-type AlGa_N buffer
layer 2 even when the Al content x therein is smaller
than 8%, by reducing the pressure in the MOVPE
process.

10 FIG.5 shows the minimum Al content x needed
for obtaining a planar and smooth top surface for the
n-type AlGa_N buffer layer 2, grown on the n-type SiC
substrate 1 by the MOVPE process, as a function of the
pressure used in the MOVPE process. More in detail,
15 the horizontal axis of FIG.5 represents the pressure
represented in Torr, while the vertical axis
represents the minimum Al content x in terms of
percent. In FIG.5, the horizontal axis and the
vertical axis are represented in a linear scale.

20 Referring to FIG.5, it will be noted that
the minimum Al content x needed for obtaining a flat
and smooth top surface for the AlGa_N buffer layer 2
decreases gradually with decreasing pressure used in
the MOVPE process along a line r_7 . In other words,
25 the relationship of FIG.5 represents the fact that the
desired flat and smooth top surface can be obtained
for the n-type AlGa_N buffer layer 2 even when the Al
content therein is small, by decreasing the pressure
in the MOVPE process.

30 In the representation of FIG.5, it should be
noted that the Al content in the vertical axis may
contain an error of about $\pm 1\%$. Thus, the deviation of
the experimental point for the pressure of 20 Torr
from the line r_7 may or may not be the result of the
35 error. It should be noted that the experimental
points for the pressure of 100 Torr, 70 Torr and 50
Torr are aligned on the line r_7 .

1 In the description hereinafter, it is noted
that the value x , indicative of the Al content in the
AlGaIn buffer layer 2 and represented in terms of
percent, includes an error of about $\pm 1\%$.

5 From the result of FIG.5, it is concluded
that the MOVPE process is conducted under a pressure
of about 90 Torr or less when to grow an AlGaIn layer
on an SiC substrate with a flat and smooth top surface
and with an Al content of about 8%. In order to grow
10 a similar AlGaIn layer with an Al content of about 6%,
on the other hand, it is preferable to conduct the
MOVPE process under a pressure of about 70 Torr or
less. Further, in order to grow a similar AlGaIn layer
with an Al content of about 4%, it is preferable to
15 conduct the MOVPE process under a pressure of about 50
Torr or less. In order to grow a similar AlGaIn layer
with an Al content of about 2%, it is preferable to
conduct the MOVPE process under a pressure of about 20
Torr or less.

20 In view of the foregoing experimental
results, it is possible to grow an n-type AlGaIn buffer
layer on an n-type SiC substrate epitaxially such that
the AlGaIn/SiC interface resistance is minimized and
simultaneously the AlGaIn buffer layer has a flat and
25 smooth top surface. By growing epitaxial layers on
the SiC substrate thus covered by the buffer layer, it
is possible to form a GaN-family laser diode having a
reduced threshold voltage. As a result of the use of
the SiC substrate, it should be noted that the laser
30 diode includes the n-side electrode formed on the SiC
substrate, similarly to a usual edge-emission type
laser diode.

FIGS.6A and 6B show the construction of a
GaN-family laser diode 100 based on the foregoing
35 experiments.

Referring to FIG.6A, the GaN-family laser
diode 100 is constructed on an n-type 6H-SiC substrate

1 31 having a Wurtzite structure and defined by a
 (0001)Si top surface. The substrate 31 is doped by n
 to a carrier density of about $8 \times 10^{17} \text{cm}^{-3}$, for
 example.

5 On the foregoing (0001)Si surface of the
 substrate 31, there is provided an n-type epitaxial
 structure 30, and an active layer structure 40 is
 formed on the epitaxial structure 30. Further,
 another epitaxial structure 50 of the p-type is formed
10 on the active layer structure 40.

 It should be noted that the n-type epitaxial
 structure 30 includes a buffer layer 32 of n-type
 AlGa_{0.09}N_{0.91} grown epitaxially on the (0001)Si surface of the substrate
15 31, another buffer layer 33 of n-type GaN formed
 epitaxially on the buffer layer 32, a cladding layer
 34 of n-type AlGa_{0.09}N_{0.91} grown epitaxially on the buffer layer
 33, and an optical waveguide layer 35 of n-type GaN
20 grown epitaxially on the cladding layer 34. The
 buffer layer 32 of the n-type AlGa_{0.09}N_{0.91} may have a
 thickness of about 0.15 μm and is doped with Si to an
 impurity concentration level of about $8 \times 10^{18} \text{cm}^{-3}$.
 The buffer layer 33, in turn, has a thickness of about
25 0.1 μm and is doped with Si to an impurity
 concentration level of about $3 \times 10^{18} \text{cm}^{-3}$. Further,
 the cladding layer 34 of n-type AlGa_{0.09}N_{0.91} has a thickness
 of typically about 0.5 μm and is doped with Si to an
 impurity concentration level of about $3 \times 10^{18} \text{cm}^{-3}$.
30 The optical waveguide layer 35 of n-type GaN has a
 thickness of about 0.1 μm and is doped with Si to a
 concentration level of about $3 \times 10^{18} \text{cm}^{-3}$.

 The active layer structure 40 forms an MQW
 (multiple quantum well) structure formed of alternate
35 and repetitive stacking of a quantum well layer of
 undoped InGa_{0.15}N_{0.85} having a composition of In_{0.15}Ga_{0.85}N
 and a barrier layer of undoped InGa_{0.15}N_{0.85} having a

1 composition of $\text{In}_{0.03}\text{Ga}_{0.97}\text{N}$, wherein the quantum well
layer typically has a thickness of about 4.0 nm while
the barrier layer has a thickness of typically about
5.0 nm. In one example, the quantum well layer is
5 repeated three times and there are provided four
barrier layers in all in the MQW active layer
structure 40.

The p-type epitaxial structure 50 includes
an electron blocking layer 51 of p-type AlGaIn having a
10 composition of $\text{Al}_{0.18}\text{Ga}_{0.82}\text{In}$ grown epitaxially on the
active layer structure 40, an optical waveguide layer
52 of p-type GaIn formed epitaxially on the electron
blocking layer 51, a cladding layer 53 of p-type AlGaIn
having a composition of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{In}$ grown
15 epitaxially on the optical waveguide layer 52, and a
contact layer 54 of p-type GaIn grown epitaxially on
the cladding layer 53. The electron blocking layer 51
of p-type AlGaIn has a large bandgap and blocks the
electrons overflowing from the active layer structure
20 40 underneath.

Typically, the electron blocking layer 51
has a thickness of about 20 nm and is doped with Mg to
an impurity concentration level of about $5 \times 10^{19} \text{cm}^{-3}$.
The GaIn optical waveguide layer 52, in turn, has a
25 thickness of about 0.1 μm and is doped with Mg to an
impurity concentration level of about $5 \times 10^{19} \text{cm}^{-3}$.
Further, the cladding layer 53 of p-type AlGaIn has a
thickness of typically about 0.5 μm and is doped with
Mg to an impurity concentration level of about $5 \times$
30 10^{19}cm^{-3} . The contact layer 54 of p-type GaIn has a
thickness of about 0.2 μm and is doped with Mg to a
concentration level of about $5 \times 10^{19} \text{cm}^{-3}$. By
providing the contact layer 54, the contact resistance
of a p-side electrode provided thereon is reduced.

35 The foregoing epitaxial layers are grown on
the SiC substrate 31 by MOVPE under a reduced pressure
of about 100 Torr. In the MOVPE process, TMG or TEG

1 is used for the gaseous source of Ga, TMA is used for
the gaseous source of Al, TMI (trimethylindium) is
used for the gaseous source of In, and NH_3 is used for
the source of N, together with the dopant gas of SiH_4
5 or biscyclopentadienyl magnesium (Cp_2Mg).

The n-type SiC substrate 31 may be formed
from a bulk crystal ingot of n-type SiC grown by an
improved Rayleigh method that uses a seed crystal.

It should be noted that the n-type epitaxial
10 structure 30 may be formed by conducting the MOVPE
process at a substrate temperature of 1090°C with a
growth rate of about $2\text{ }\mu\text{m}/\text{H}$. On the other hand, the
MQW structure of the active layer structure 40 may be
formed by conducting the MOVPE process at a substrate
15 temperature of 780°C with a growth rate of about 0.3
 $\mu\text{m}/\text{H}$. Further, the p-type epitaxial structure 50 may
be formed by conducting the MOVPE process at a
substrate temperature of 1130°C with a growth rate of
about $1\text{ }\mu\text{m}/\text{H}$.

20 In the GaN-family laser diode 100 thus
obtained, it should be noted that the AlGaN/SiC
interface resistance at the interface between the n-
type SiC substrate 31 and the n-type AlGaN buffer
layer 32 is successfully suppressed in view of the
25 fact that the n-type AlGaN buffer layer 32 having the
composition of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ contains the n-type
carriers with the carrier density of about $8 \times 10^{18}\text{cm}^{-3}$.
See the diagram of FIG.2B. It should be noted
that the thickness of the n-type SiC substrate 31 may
30 be reduced, from an initial thickness of about $200\text{ }\mu\text{m}$,
to about $100\text{ }\mu\text{m}$ by polishing the rear surface thereof.

After the formation of the epitaxial
structures 30, 40 and 50 on the Si substrate 31, the
epitaxial structures are subjected to a dry etching
35 process and a mesa structure having a width of $3 - 5$
 μm , typically $3.5\text{ }\mu\text{m}$, is formed to extend in the axial
direction of the laser diode with a height of about

1 0.4 μm . As a result of the mesa formation, there is
formed a refractive optical guide structure in the
cladding layer 53 wherein the optical guide structure
thus formed controls the transverse mode of laser
5 oscillation.

After the mesa formation, an insulation film
61 of SiO_2 is formed so as to cover the mesa structure
thus formed in the cladding layer 53 and the contact
layer 54, followed by formation of a contact window in
10 the insulation film 61 so as to expose the contact
layer 54. The contact window thus formed may have a
width of 1 - 4 μm .

After the step of formation of the contact
window, an n-side electrode 63 is formed on the SiC
15 substrate 31 by depositing a Ni layer, a Ti layer and
a Au layer consecutively on the bottom surface of the
SiC substrate. Further, a p-side electrode 62 is
formed on the mesa structure by depositing a Ni layer,
a Ti layer and a Au layer consecutively.

20 The structure thus obtained is then
subjected to a cleaving process in the direction
perpendicular to the elongating direction of the mesa
structure, in other words the axial direction of the
laser diode, to form a ridge-type cavity having a
25 length of about 700 μm as represented in FIG.6B. It
should be noted that the ridge-type cavity extends in
the $\langle 1100 \rangle$ direction of the SiC substrate 31, while
the cleavage surface has an orientation of $[1100]$. In
the structure of FIG.6B, mirrors HR are formed on the
30 cleaved surfaces.

It was confirmed that the GaN-family laser
diode 100 thus formed oscillates at the optical
wavelength of 420 nm when driven by a pulse generator
at a frequency of 1 kHz - 10 kHz. Thereby, it was
35 observed that the threshold current is about 500 mA
and the threshold voltage is about 15V.

For the sake of comparison, a laser diode

1 similar to the GaN-family laser diode 100 was
fabricated in which the carrier density of the n-type
AlGaIn buffer layer 32 is set to $3 \times 10^{18} \text{cm}^{-3}$ while
maintaining the composition of the buffer layer 32 to
5 $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$. In this experiment, although it was
confirmed that the laser diode oscillates at the
optical wavelength of 420 nm, the threshold voltage
has increased to 22V. The threshold current remained
the same and took the value of 500 mA. The foregoing
10 result indicates that the threshold voltage of the
laser diode is reduced from 22V to 15V, by increasing
the carrier density in the n-type AlGaIn buffer layer
32 having the composition of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ from $3 \times$
 10^{18}cm^{-3} to $8 \times 10^{18} \text{cm}^{-3}$.

15 Further, another experiment was conducted by
fabricating a laser diode similar to the laser diode
100 except that the carrier density in the n-type SiC
substrate 31 is increased from $8 \times 10^{17} \text{cm}^{-3}$ to $4 \times$
 10^{18}cm^{-3} .

20 It was confirmed that the laser diode thus
formed oscillates at the optical wavelength of 420 nm
similarly to the laser diode 100 and that the
threshold voltage was decreased to 12V, indicating a
further decrease by 3V as compared with the laser
25 diode 100. The threshold current remained the same.

In view of the relationship of FIG.2B, it is
expected that the threshold voltage may be decreased
further by increasing the carrier density in the n-
type AlGaIn buffer layer 32. Further, the relationship
30 of FIG.4 indicates that the AlGaIn/SiC interface
resistance, and hence the threshold voltage of the
laser diode, is reduced further by reducing the Al
content in the AlGaIn buffer layer 32 below the value
of 0.09.

35 In order to maintain the flat and smooth
surface for the AlGaIn buffer layer 32 for the case in
which the Al content is reduced, it is preferable to

1 conduct the MOVPE process for forming the AlGa_N buffer
layer 32 under a reduced pressure environment, in view
of the relationship of FIG.5. For example, the buffer
layer 32 may be formed to have a composition
5 Al_{0.04}Ga_{0.96}N in place of the composition of
Al_{0.09}Ga_{0.91}N by conducting the MOVPE process under
the pressure of 40 Torr. Other epitaxial layers are
formed similarly to the case of the laser diode 100.

When the Si concentration level of $8 \times$
10 10^{18} cm^{-3} is used in the n-type AlGa_N buffer layer 32
in combination with the foregoing composition of
Al_{0.04}Ga_{0.96}N, it is expected that the threshold
voltage decreased to about 10V. By further reduction
of the Al content in the n-type AlGa_N buffer layer 32,
15 the AlGa_N/SiC interface resistance, and hence the
threshold voltage, would be reduced further.

[SECOND EMBODIMENT]

During the experimental investigation on the
20 Ga_N-family laser diode 100 described with reference to
FIGS.6A and 6B, the inventor of the present invention
has discovered a relationship shown in FIG.7 between
the threshold current and the thickness of the
epitaxial layers interposed between the SiC substrate
25 41 and the active layer structure 40, wherein the
vertical axis represents the threshold current density
of the laser diode while the horizontal axis
represents the total thickness of the epitaxial layers
interposed between the SiC substrate 31 and the active
30 layer structure 40.

Referring to FIG.7, the threshold current
generally decreases with increasing thickness in the
epitaxial layers interposed between the substrate 31
and the active layer 40 and that the decrease occurs
35 sharply until the total thickness of the epitaxial
layers reach the value of about 1.6 μm .

While the reason of this phenomenon is not

1 clearly understood, it is probable that the defect
density in the epitaxial layers decreases with
increasing total thickness of the epitaxial layers
between the substrate 31 and the active layer
5 structure 40.

Thus, in view of the relationship of FIG.7,
it is concluded that the threshold current of the
laser diode can be reduced by increasing the total
thickness of the epitaxial layers interposed between
10 the substrate 31 and the active layer structure 40.
On the other hand, there arises a problem of cracking
in the epitaxial structure 30, 40 or 50 when the
foregoing total thickness is increased excessively,
probably due to the tensile stress caused as a result
15 of the difference in thermal expansion between the SiC
substrate 31 and the nitride epitaxial layers thereon.

The inventor of the present invention has
discovered that the cracking of the epitaxial
structures is effectively suppressed by setting the Al
20 content y of the lower cladding layer 34 of n-type
 AlGa_yN having a composition represented as $\text{Al}_y\text{Ga}_{1-y}\text{N}$,
to be smaller than the Al content x of the foregoing
n-type AlGaN buffer layer 32, of which composition is
represented as $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($y < x$). Further, the
25 inventor of the present invention has discovered that
the problem of cracking of the epitaxial layers is
further suppressed by setting the Al content z of the
upper cladding layer 53 of p-type AlGaN having a
composition represented as $\text{Al}_z\text{Ga}_{1-z}\text{N}$, to be smaller
30 than the Al content y in the lower cladding layer 34
($z < y$). It is believed that the foregoing
suppression of the crack formation in the epitaxial
layers is achieved as a result of cancellation of the
tensile stress, which is induced in the epitaxial
35 layer by the differential thermal expansion of the SiC
substrate 31 and the epitaxial layers, by a
compressive stress. It should be noted that the

1 foregoing compressive stress is induced in the
epitaxial layers including the buffer layer 32 and the
cladding layers 34 and 53 as a result of the
difference in the lattice constant between the SiC
5 substrate 31 and the epitaxial layers thereon.

FIG.8 shows the construction of a laser
diode 200 according to a second embodiment of the
present invention, wherein those parts corresponding
to the part described previously are designated by the
10 same reference numerals and the description thereof
will be omitted.

Referring to FIG.8, the laser diode 200 has
a construction in which the GaN buffer layer 33 is
omitted, and the AlGaIn buffer layer 32, the AlGaIn
15 cladding layer 34 and the GaN optical waveguide layer
35 are formed to have respective thicknesses of 1.0
 μm , 1.5 μm and 0.1 μm . As a result, the total
thickness of the epitaxial layers interposed between
the SiC substrate 31 and the active layer structure 40
20 takes a value of 2.6 μm , and the threshold current
density of laser oscillation 200 is reduced to about 7
- 8 kA/cm^2 .

In the present embodiment, it should be
noted that the lower cladding layer 34 of n-type AlGaIn
25 contains Al with an atomic fraction y of 0.10 ($y =$
0.10), while this value of the Al content y is smaller
than the Al content x of 0.15 ($x = 0.15$) of the n-type
AlGaIn buffer layer 32. Further, it should be noted
that the upper cladding layer 53 of p-type AlGaIn
30 contains Al with an atomic fraction z of 0.08 ($z =$
0.08), while this value z of the Al content of the
upper cladding layer 53 is smaller than the foregoing
value y for the lower cladding layer 34.

As a result of the foregoing construction,
35 the laser diode 200 of the present embodiment
successfully eliminates the crack formation in the
epitaxial layers.

1 Other features of the present embodiment are
substantially the same as those of the laser diode 100
described previously and further description thereof
will be omitted.

5 FIG.9 shows the construction of a laser
diode 210 corresponding to a modification of the laser
diode 210 of the present embodiment, wherein those
parts corresponding to the parts described previously
are designated by the same reference numerals and the
10 description thereof will be omitted.

 In the present modification, the buffer
layer 32, the cladding layer 34 and the optical
waveguide layer 35 are formed to have respective
thicknesses of 0.35 μm , 1.15 μm and 0.1 μm , thus
15 leading to the total thickness of 1.6 μm for the
epitaxial layers interposed between the SiC substrate
31 and the active layer structure 40. In the present
modification, the buffer layer 32 and the lower
cladding layer 34 are formed to have the same Al
20 content of 0.10 for the compositional parameters x and
y, while the upper cladding layer 53 contains Al with
a reduced content of 0.08 for the compositional
parameter z. Thereby, the problem of cracking of the
epitaxial layers is suppressed effectively also in the
25 present modification.

[THIRD EMBODIMENT]

 In the ridge-type laser diode 100, 200 or
210 described before, the control of transversal mode
30 laser oscillation in the active layer structure 40 is
achieved by forming a mesa structure in the upper
cladding layer 53 as explained before.

 In the ridge-type laser diode having such a
structure, it is necessary to form the mesa structure
35 to have a width of less than about 2 μm in order to
achieve a satisfactory control of the transversal mode
oscillation, while the formation of such a narrow mesa

1 structure has been difficult. Further, the foregoing
conventional ridge-type laser diode has a drawback in
that the contact area between the electrode 62 and the
contact layer 54 is reduced inevitably when the width
5 of the mesa structure is thus reduced below 2 μm . It
should be noted that the width of the contact window
formed in the SiO_2 film 61 is reduced together with
the width of the mesa structure, while formation of
such a very small contact window in the SiO_2 film 61
10 on the mesa structure raises various problems.

Further, the ridge-type laser diodes have a
further drawback in that the confinement of the
optical radiation inside the active layer structure 40
in the vertical direction tends to become weak and
15 insufficient. In order to realize a satisfactorily
strong optical confinement in the active layer
structure 40, it is necessary to increase the
thickness of the upper cladding layer 53 further,
while such an increase of thickness of the upper
20 cladding layer 53 tends to cause a cracking therein.
It should be noted that the cladding layer 53 has a
lattice constant different from that of the buffer
layer 32. In view of insufficient optical confinement
in the active layer structure 40, the ridge-type laser
25 diodes including the laser diodes 100, 200 and 210
tend to show the problem of optical loss caused by the
electrode 62 or poor far-field pattern (FFP) in the
optical beam produced by the laser diode.

FIGS.10A and 10B show a fabrication process
30 of a laser diode 300 wherein the foregoing problems
are eliminated, wherein those parts corresponding to
the parts described previously are designated by the
same reference numerals and the description thereof
will be omitted.

35 Referring to FIG.10A, the laser diode 300 is
constructed on the n-type SiC substrate 31 carrying
thereon the n-type epitaxial structure 30, the active

1 layer structure 40 and the p-type epitaxial structure
50 similarly to the laser diodes of the previous
embodiments, wherein the mesa formation in the upper
cladding layer 53 or the contact layer 54 forming a
5 part of the p-type epitaxial structure 50 is omitted.
It should be noted that the n-type epitaxial structure
30 includes the n-type nitride layers 32 - 35 while
the p-type epitaxial structure includes the p-type
nitride layers 51 - 54 similarly as before. As a
10 result, the contact layer 54 has a flat top surface
and an insulation film 301 of SiO_2 is formed on the
flat top surface of the contact layer 54 by a high-
temperature CVD process with a thickness of about 300
nm.

15 The SiO_2 film 301 is then patterned by a
photolithographic process using HF as an etchant to
form a stripe opening 301W in the SiO_2 film 301 with a
width of about 1 μm , wherein the stripe opening 301W
is formed so as to extend in the axial direction of
20 the laser diode 300 coincident with the $\langle 1100 \rangle$
direction of the SiC substrate 31.

Next, in the step of FIG.10B, the deposition
of a p-type AlGaIn layer having a composition of
 $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ is made on the exposed part of the GaN
25 cap layer 54 exposed at the foregoing stripe opening
301W by an MOVPE process while using the SiO_2 film 301
as a mask, to form a third cladding layer 302 with a
thickness of about 1.4 μm . It should be noted that
the MOVPE process is conducted under a condition
30 similar to the condition used for forming the
epitaxial layers in the p-type epitaxial structure 50.
The third cladding layer 302 thus grow not only in the
upward direction but also in lateral directions to
form a ridge structure covering the insulation film
301 and extending thereon in the axial direction of
35 the laser diode.

Next, in the step of FIG.10B, a contact

1 layer 303 of p-type GaN is formed on the third
cladding layer 302 by an MOVPE process with a
thickness of about 0.2 μm so as to cover both side
walls and a top surface thereof continuously, and the
5 electrode 62 is deposited so as to cover the contact
layer 303 continuously over a part corresponding to
the side walls and the top surface of the underlying
third cladding layer 302. Further, the bottom surface
of the n-type SiC substrate 31 is polished and the
10 electrode 63 is formed on the bottom surface of the
SiC substrate 31 thus polished, similarly to the
embodiments described before.

According to the laser diode 300 of the
present embodiment, the photolithographic patterning
15 process of the insulation film 301 is conducted in the
step of FIG.10A on the flat, planar principal surface
of the GaN cap layer 54. Thereby, the patterning
process is under an ideal condition with an excellent
precision and the stripe opening 301W is formed
20 relatively easily to have a width of less than 1 μm .

In the present embodiment, it should be
noted that the cap layer 54 of GaN is provided for
preventing the oxidation of the AlGaIn cladding layer
53 when forming the insulation film 301. The
25 insulation film 301 is by no means limited to SiO_2 but
other materials such as SiN or Al_2O_3 may also be used.

It should be noted that the structure of the
present embodiment is applicable also to the
conventional laser diode constructed on a sapphire
30 substrate such as the one described with reference to
FIG.1. When using a sapphire substrate, the stripe
opening 301W is formed in the insulation film 301 so
as to extend in the $\langle 11\bar{2}0 \rangle$ direction of the sapphire
substrate corresponding to the $\langle 1\bar{1} \rangle$ direction of a GaN
35 crystal.

According to the laser diode 300 of the
present embodiment, in which the electrode 62 covers

1 the top surface and both side walls of the third
cladding layer 302 continuously via the contact layer
303, the contact resistance of the electrode 62 is
reduced substantially. Further, in view of the fact
5 that the injection of carriers (holes) into the active
layer structure 40 is restricted to the foregoing
elongating stripe opening 301W, the desired current
confinement in the active layer structure 40 is
achieved effectively without restricting the width of
10 the cladding layer 302 strictly. Thereby, an
effective control of the transverse mode becomes
possible.

As the cladding layer 302 is formed as a
result of the selective growth of the AlGaIn layer
15 occurring in the narrowly confined stripe opening
301W, there occurs no substantial problem of
relaxation of crystal lattice in the AlGaIn cladding
layer 302 and the crack formation does not occur in
the cladding layer 302 even when the third cladding
20 layer 302 is formed to have an increased thickness.
Thereby, an excellent optical confinement is realized
in the vertical direction and the far-field pattern of
the laser diode is improved substantially. Further,
the problem of optical loss caused by the electrode 62
25 is also reduced.

In the step of FIG.10B, there may be a case
in which particles are formed on the insulation film
301 during the process of forming the cladding layer
302 or the contact layer 303 by the selective growth
30 process. It should be noted that the insulation film
301 is used in the foregoing selective growth process
as a mask. When there occurs such a deposition of
particles on the insulation film 301, the adherence of
the electrode 62 may be deteriorated.

35 In order to avoid the foregoing risk of
deterioration of adherence of the electrode 62, the
SiO₂ film 301 may be removed by a wet etching process

1 after the formation of the cladding layer 301 and the
contact layer 303 by using a suitable etchant such as
HF. As a result of removal of the SiO_2 film 301, the
particles deposited thereon are also removed.

5 FIG.11 shows the construction of a laser
diode 310 thus formed according to a modification of
the present embodiment.

Referring to FIG.11, the third cladding
layer 302 has a T-shaped form having a reduced width
10 at the bottom part thereof similarly to the structure
of FIG.10B, wherein it should be noted that the SiO_2
film 301 of FIG.10B is replaced with an air gap 301G
cutting into the cladding layer 302 from both lateral
sides thereof at the bottom part of the cladding layer
15 302. Further, an SiO_2 film similar to the SiO_2 film
61 is provided so as to cover the top surface and both
side walls of the cladding layer 302 wherein the SiO_2
film 61 covers the exposed top surface of the contact
layer 54. The contact laser 61 is formed with an
20 opening exposing the GaN contact layer 303 covering
the top surface of the third cladding layer 302 and
the electrode 62 makes an ohmic contact with the
exposed top surface of the third cladding layer 302.

Typically, the SiO_2 film 61 is formed by a
25 vapor phase deposition process such as a high-
temperature CVD process and may penetrate into the air
gap 301G. Thereby, the air gap 301G may be filled
entirely or partially by SiO_2 forming the SiO_2 film
61.

30 In the laser diode 300 or 310 of the present
embodiment, it is possible to eliminate the contact
layer 303.

[FOURTH EMBODIMENT]

35 FIG.12A is a plan view showing the
insulation film 301 used as a mask in the foregoing
fabrication process of the laser diode 300 or 310,

1 when forming the cladding layer 302 or 303 by a
selective growth process.

Referring to FIG.12A, the insulation film
301 includes a number of linearly extending stripe
5 openings each having a width of about 1 μm . The
stripe openings are repeated with an interval of about
300 μm , and thus, there is formed a wide area of SiO_2
between one stripe opening and an adjacent stripe
opening.

10 Thus, it will be easily understood that
there occur an extensive formation of particles on the
mask when the insulation film 301 of FIG.12A is used
for the mask during the MOVPE process for forming the
third cladding layer 302 or the contact layer 303.

15 In the present embodiment, the foregoing
problem of deposition of particles on the mask is
eliminated by using a mask 301A shown in FIG.12B.

Referring to FIG.12B, it will be noted that
a pair of linearly extending insulation stripes 301a
20 and 301b each having a width of 6 μm are disposed
adjacent with each other to form a mask pattern 301c,
with a gap 301n of about 1 μm formed between the
insulation stripes 301a and 301b forming the mask
pattern 301c, wherein the foregoing mask pattern 301c
25 thus formed is repeated a number of times with a pitch
of 300 μm . In the mask 301A thus including the
repetition of the mask patterns 301c, it should be
noted that the underlying GaN contact layer 54 is
exposed between a mask pattern 301c and an adjacent
30 mask pattern 301c, and the problem of particle
formation is effectively eliminated. Instead of
forming particles, the source elements supplied during
the MOVPE process for forming the p-type AlGaN
cladding layer 302 or the p-type GaN contact layer 303
35 form an epitaxial layer of p-type AlGaN or p-type GaN
on the exposed surface of the GaN contact layer 54.

FIG.13 shows the construction of a laser

1 diode 400 that uses the mask 301A of FIG.12B for the
selective growth process of the third cladding layer
302 and the contact layer 303 according to a fourth
embodiment of the present invention, wherein those
5 parts corresponding to the parts described previously
are designated by the same reference numerals and the
description thereof will be omitted.

Referring to FIG.13, the mask 301A is formed
on the contact layer 54 of p-type GaN, and the
10 cladding layer 302 of p-type AlGaIn and the contact
layer 303 of p-type GaN are formed consecutively on
the contact layer 54 in correspondence to the stripe-
formed gap 301n of the mask pattern 301c, by
conducting the MOVPE process while using the mask 301A
15 as a mask. Simultaneously, an epitaxial layer 302A of
p-type AlGaIn having a composition substantially
identical with the composition of the cladding layer
302 is formed outside the mask pattern 301c, and
another epitaxial layer 303A of p-type GaN having a
20 substantially identical composition with the
composition of the contact layer 303 is formed on the
epitaxial layer 302A. Thereby, the epitaxial
structure including the epitaxial layers 302A and 303A
is separated from the structure formed of the third
25 cladding layer 302 and the contact layer 303 by a
recess exposing the mask 301A.

It should be noted that the epitaxial layer
303A is covered by another SiO_2 film 304, wherein the
 SiO_2 film 304 includes an opening formed in
30 correspondence to the recess part so as to expose the
contact layer 303, and an electrode corresponding to
the electrode 62 is formed on the SiO_2 film 304 so as
to fill the foregoing recess. It should be noted that
the SiO_2 film 304 is formed to have a thickness of
35 about 200 nm by a high-temperature CVD process, and
the foregoing opening is formed in the SiO_2 film 304
by a wet etching process using HF.

1 As explained already, the laser diode 400 of
the present embodiment minimizes the formation of
particles on the mask 301A and the yield of production
of the laser diode is improved substantially. As the
5 laser diode 400 of FIG.13 allows the electrode 62 to
have a large area and a substantially flat top
surface, mounting process of the laser diode 400 is
facilitated substantially.

10 [FIFTH EMBODIMENT]

As explained already, the selective growth
process used in the fabrication process of the laser
diode 300, 310 or 400 tends to cause the problem of
deposition of particles on the insulation mask. This
15 problem of particle formation becomes particularly
serious in the process of forming the cladding layer
302 of AlGaN. It should be noted that the AlN
component included in the AlGaN cladding layer 301 has
a tendency of preferential deposition on an SiO₂ film
20 that forms the mask 301, while the AlN component thus
deposited tend to act as a nucleus for formation of
the AlGaN cladding layer 301.

In the experimental investigation that
constitutes the basis of the present invention, the
25 inventor of the present invention has discovered that
the formation of particles on an SiO₂ mask is
effectively suppressed in the selective growth process
of AlGaN conducted by an MOVPE process, by supplying
the gaseous source of the elements together with a gas
30 containing halogen.

FIGS.14A - 14F explain the foregoing
experiments conducted by the inventor of the present
invention.

Referring to FIG.14A, a 6H-SiC substrate 501
35 is cleaned in an organic solvent and then in water,
and the substrate 501 thus processed is then immersed
in a bath of HF for about 1 minute.

1 The substrate 501 thus processed is then
introduced into a reaction chamber of an MOVPE
apparatus so as to expose a (0001)Si surface thereof
on which the deposition of epitaxial layers is to be
5 made. After evacuating the reaction chamber, the
native oxide film is removed from the surface of the
SiC substrate 501 by processing the substrate 501 at
1080°C in a hydrogen atmosphere for about 5 minutes.
Next, the substrate temperature is reduced to about
10 1050°C, and an AlGaN film 502 is grown on the
foregoing (0001)Si surface of the substrate 501 while
supplying TMG, TMA and NH₃ with respective flow rates
of 44 μmol/min, 8 μmol/min and 0.1 μmol/min, together
with a carrier gas of H₂. The foregoing source gases
15 are applied directly to the substrate surface and the
AlGaN film 502 is grown thereon with a thickness of
about 1 μm.

Next, in the step of FIG.14B, the supply of
TMG and TMA is interrupted and the substrate
20 temperature is lowered to 600°C or lower while
continuously directing the NH₃ gas to the substrate.
Thereby, the atmosphere inside the reaction chamber is
changed to N₂. After cooling further to the room
temperature, the substrate 501 is taken out from the
25 deposition chamber, and an SiO₂ film 503 is formed on
the foregoing AlGaN film 502 with a thickness of 0.2
μm.

Next, in the step of FIG.14C, a resist film
is formed on the SiO₂ film 503, followed by a
30 patterning process to form a resist pattern 504 having
a width of 2 μm, such that the resist pattern 504 is
repeated with a pitch of 30 μm.

Next, in the step of FIG.14D, the SiO₂ film
is subjected to a wet etching process using HF as an
35 etchant to form a line and space pattern exposing the
AlGaN film 502. After removing the resist pattern 504
by using an organic solvent, the substrate 501 is

1 returned to the reaction chamber of the MOVPE
apparatus. The reaction chamber is then evacuated,
and the native oxide film is removed from the exposed
part of the AlGaIn film 502 by applying a heat
5 treatment process at 1050°C in H₂ atmosphere, while
supplying NH₃. Further, a selective epitaxial growth
of an AlGaIn film 505 is made on the exposed surface of
the AlGaIn film 502 by supplying TMG, TMA, CH₃Cl and
NH₃ with respective flow rates of 44 μmol/min, 8
10 μmol/min, 52 μmol/min and 0.1 μmol/min, together with
a carrier gas of H₂.

In the step of FIG.14F, the substrate
temperature is then lowered to below 600°C while
supplying NH₃ to the reaction chamber, such that the
15 atmosphere inside the reaction chamber is changed to
the N₂ atmosphere. Thereafter, the substrate
temperature is lowered to the room temperature.

According to the selective growth process of
the present embodiment, the CH₃Cl molecules supplied
20 in the step of FIG.14F to the reaction chamber
together with the gaseous source material release Cl
atoms as a result of the pyro-decomposition process
thereof, wherein the Cl atoms thus released suppresses
the AlN formation on the exposed surface of the AlGaIn
25 film 502 by preferentially reacting with Al. The
supply of CH₃Cl is preferably made to the reaction
chamber by a gas inlet different from the inlet used
for introducing a gaseous source of group V element
such as NH₃. Thereby, the nuclei formation on the
30 SiO₂ mask 503 is impeded and the deposition of
polycrystalline or particulate precipitates on the
mask 503 is suppressed.

It should be noted that the element that
suppresses the AlN formation on the SiO₂ mask is by no
35 means limited to Cl but other halogen element such as
F can be used also for the same purpose. Further, the
compound that is used as the carrier of the halogen

1 atom is by no means limited to CH_3Cl but other halogen
compounds, including a metal-organic compound
containing halogen, may also be used.

It should be noted that the selective
5 epitaxial growth process according to the present
embodiment is applicable not only to the fabrication
process of a ridge-type laser diode as described but
the present embodiment is also applicable to general
fabrication process of a semiconductor device that
10 includes a selective growth of a nitride film of a
group III element including Al.

[SIXTH EMBODIMENT]

In the GaN-family laser diodes 100, 200,
15 300, 310 and 400 described heretofore, it should be
noted that there is formed an electron blocking layer
51 of AlN formed adjacent to the active layer
structure 40, wherein the electron blocking layer 51
is doped with Mg to a high concentration level and
20 blocks the electrons that are injected into the active
layer structure 40 and subsequently causing an
overflow from the active layer structure 40 as a
result of the large electric field formed in the p-
type epitaxial structure 50. For this purpose, the
25 electron blocking layer 51 is generally formed to have
a composition that provides a large bandgap. Thus,
the optical waveguide layer 52 of p-type GaN or the
cladding layer 53 of p-type AlGaIn is formed above the
electron blocking layer 51. It should be noted that
30 the p-type AlGaIn cladding layer 53 has a relatively
large resistivity, and because of this, the foregoing
large electric is created.

FIG.15 shows the Mg concentration profile
used in the GaN-family laser diode disclosed in the
35 Japanese Laid-Open Patent Publication 10-56236 for the
part located above the active layer structure. It
should be noted that the GaN-family laser diode of

1 FIG.15 is formed on a sapphire substrate.

Referring to FIG.15, the laser diode includes, in addition to the foregoing electron blocking layer, an optical waveguide layer of GaN
5 formed thereon as a part of the SCH structure and a cladding layer of AlGa_N, wherein the electron blocking layer, the optical waveguide layer and the cladding layer are all doped with Mg to the concentration level of about $5 \times 10^{19} \text{cm}^{-3}$. Only the uppermost contact
10 layer of GaN is doped by Mg to the concentration level of about $1 \times 10^{20} \text{cm}^{-3}$. It should be noted that the laser diode 100 of the previous embodiment also uses the Mg profile of FIG.15.

On the other hand, the Mg concentration
15 profile of FIG.15 cannot avoid cracking in the epitaxial layers used in nitride laser diodes. Such cracks formed in the epitaxial layers provides undesirable effect of decreased efficiency of laser oscillation and increased threshold voltage. Thus, it
20 is desirable to reduce the crack formation as much as possible.

In the experimental investigation on the laser diode 100 described previously, the inventor of the present invention has discovered that the cracks
25 formed in the epitaxial layers of the laser diode is reduced substantially when the Mg concentration level is reduced in the p-type GaN optical waveguide layer 52 and the p-type AlGa_N cladding layer 53, all located above the active layer structure 40.

30 Referring to FIG.16, it can be seen that the crack density observed on the surface of the cladding layer 53 is reduced sharply when the Mg concentration level in the GaN optical waveguide layer 52 and the AlGa_N cladding layer 53 is reduced below the
35 conventionally used value of $5 \times 10^{19} \text{cm}^{-3}$. When the Mg concentration level is reduced below about $4 \times 10^{19} \text{cm}^{-3}$, particularly below than about $3 \times 10^{19} \text{cm}^{-3}$,

1 it can be seen that the observed crack density becomes
substantially zero. In FIG.16, it should be noted
that the vertical axis represents the crack density
while the horizontal axis represents the Mg
5 concentration level.

In conformity with the crack density, the
resistance of the laser diode 100 is reduced sharply
when the Mg concentration level in the optical
waveguide layer 52 and the cladding layer 53 is
10 reduced. Thereby, a minimum resistance is reached
when the optical waveguide layer 52 and the cladding
layer 53 have the Mg concentration level of $3 - 4 \times 10^{19} \text{cm}^{-3}$
as represented in FIG.17, wherein FIG.17
shows the Mg concentration level in the horizontal
15 axis and the drive voltage necessary for flowing a
drive current of 100 mA in the vertical axis. With
further decrease in the Mg content, it can be seen
that the resistance of the laser diode 100 starts to
increase again, while this effect is merely attributed
20 to the depletion of carriers in the optical waveguide
layer 52 and in the cladding layer 53 due to the
excessively reduced concentration level of Mg.

FIG.18 shows the doping profile of Mg for
the laser diode 100 of FIGS.6A and 6B optimized in
25 view of the discovery of the relationship of FIG.17.

Referring to FIG.18, the electron blocking
layer 51 of p-type AlGa_N has a composition of
Al_{0.18}Ga_{0.82}N and is formed on the active layer
structure 40 with a thickness of about 20 nm, wherein
30 the electron blocking layer 51 is doped with Mg to the
concentration level of about $1 \times 10^{20} \text{cm}^{-3}$. On the
electron blocking layer 51, the optical waveguide
layer 52 of p-type GaN is formed with a thickness of
about 100 nm, wherein the optical waveguide layer 52
35 is doped with Mg to the concentration level of about $4 \times 10^{19} \text{cm}^{-3}$. Further, the cladding layer 53 of p-type
AlGa_N has a composition of Al_{0.09}Ga_{0.91}N as noted

1 before wherein the cladding layer 53 is formed on the
optical waveguide layer 52 with a thickness of about
550 nm. The cladding layer 53 is also doped with Mg
to the concentration level of about $4 \times 10^{19} \text{cm}^{-3}$.

5 On the cladding layer 53, the contact layer
54 of p-type GaN is formed with a thickness of about
80 nm, wherein the contact layer 53 is doped with Mg
to the concentration level of about $1.5 \times 10^{20} \text{cm}^{-3}$.

According to the present invention, the
10 crack density in the optical waveguide layer 52 and
the cladding layer 53 is minimized by setting the Mg
concentration level in the layers 52 and 53 to be
about $4 \times 10^{19} \text{cm}^{-3}$ or less. Thereby, the resistance
of the laser diode is minimized. Further, the
15 threshold voltage of the laser diode is decreased by
increasing the Mg concentration level in the electron
blocking layer 51 above the foregoing value of about 4
 $\times 10^{19} \text{cm}^{-3}$. Further, the increase of the laser diode
resistance as a result of the excessively low impurity
20 concentration level is also avoided.

FIG.19 shows a modification of the
embodiment of FIG.18 in which the Mg concentration
level in the optical waveguide layer 52 and the
cladding layer 53 is decreased to about $3 \times 10^{19} \text{cm}^{-3}$
25 in view of the relationship of FIG.17. In the case of
FIG.19, too, the crack density in the epitaxial layers
constituting the laser diode 100 is reduced to
substantially zero by combining the electron blocking
layer 51 and the contact layer 54, which are doped to
30 a high concentration level. Thereby, the crack
density, and hence the resistance, in the epitaxial
layers is successfully minimized.

Further, the present invention is not
limited to the embodiments described heretofore, but
35 various variations and modifications may be made
without departing from the scope of the invention.

The present application is based on Japanese

1 priority applications No.10-135425 and 10-353241 filed
respectively on May 18, 1998 and December 11, 9998,
the entire contents of which are hereby incorporated
by reference.

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1 WHAT IS CLAIMED IS

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1. An optical semiconductor device,
comprising:

a substrate of SiC having a first
conductivity type;

10 a buffer layer of AlGa_N formed on said
substrate epitaxially, said buffer layer having said
first conductivity type and a composition represented
by a compositional parameter x as Al _{x} Ga_{1- x} N;

a first cladding layer having said first
15 conductivity type, said first cladding layer being
formed on said buffer layer epitaxially;

an active layer formed epitaxially on said
first cladding layer;

a second cladding layer having a second,
20 opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;

a first electrode provided so as to inject
first-type carriers having a first polarity into said
second cladding layer; and

25 a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,

said buffer layer containing said first type
carriers with a concentration level in the range from
30 $3 \times 10^{18} \text{cm}^{-3}$ to $1 \times 10^{20} \text{cm}^{-3}$ and said compositional
parameter x larger than 0 but smaller than 0.4 ($0 < x$
<0.4).

35

2. An optical semiconductor device as

1 claimed in claim 1, wherein said substrate contains
carriers of said first conductivity type with a
concentration level in the range from 1×10^{18} - $1 \times$
5 10^{20}cm^{-3} .

3. An optical semiconductor device as
10 claimed in claim 1, wherein said compositional
parameter x of said buffer layer is less than 0.09 (x
< 0.09).

15
4. An optical semiconductor device as
claimed in claim 1, wherein said substrate has a
(0001)Si surface of SiC and wherein said buffer layer
20 is formed on said (0001)Si surface in intimate contact
with said substrate.

25
5. A method of fabricating an optical
semiconductor device, comprising the step of: growing
an AlGa_xN film having a composition of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ ($0 < x$
< 0.4) on an SiC substrate by a metal-organic vapor
30 phase epitaxy process, under a pressure of about 90
Torr or less.

35
6. An optical semiconductor device,
comprising:

- 1 a substrate of SiC having a first conductivity type;
a buffer layer of AlGa_N formed on said substrate epitaxially;
- 5 a first cladding layer of AlGa_N having said first conductivity type, said first cladding layer being formed on said buffer layer epitaxially;
an optical waveguide layer of Ga_N having said first conductivity type, said optical waveguide
- 10 layer being formed on said first cladding layer epitaxially;
an active layer formed epitaxially on said optical waveguide layer, said active layer containing Ga as a group III element and N as a group V element;
- 15 a second cladding layer of AlGa_N having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;
a first electrode provided so as to inject
- 20 first-type carriers having a first polarity into said second cladding layer; and
a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,
- 25 said substrate having a top surface separated from a bottom surface of said active layer by a distance of about 1.6 μm or more.

30

7. An optical semiconductor device as claimed in claim 6, wherein said buffer layer has a composition represented by a compositional parameter x
- 35 as $\text{Al}_x\text{Ga}_{1-x}\text{N}$, said first cladding layer has a composition represented by a compositional parameter y as $\text{Al}_y\text{Ga}_{1-y}\text{N}$, and said second cladding layer has a

1 composition represented by a compositional parameter z
as $\text{Al}_z\text{Ga}_{1-z}\text{N}$, said compositional parameter x having a
value equal to or larger than 0.08 but smaller than
0.5 ($0.08 \leq x < 0.5$), said compositional parameter y
5 having a value equal to or larger than 0.05 but equal
to or smaller than said compositional parameter x
($0.05 \leq y \leq x$), said compositional parameter z having
a value smaller than said compositional parameter y (z
< y).

10

8. An optical semiconductor device,
15 comprising:
a substrate of SiC having a first
conductivity type;
a first cladding layer having a first
conductivity type, said first cladding layer being
20 formed on said substrate epitaxially;
an active layer formed epitaxially on said
first cladding layer;
a second cladding layer having a second,
opposite conductivity type, said second cladding layer
25 being formed on said active layer epitaxially;
a third cladding layer having said second
conductivity type, said third cladding layer being
formed on said second cladding layer epitaxially;
a first electrode provided so as to inject
30 first-type carriers having a first polarity into said
second cladding layer; and
a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,
35 said third cladding layer having a ridge
structure,
wherein an insulating film is interposed

1 between said second cladding layer and said third
cladding layer, said insulating film having an opening
in correspondence to said ridge structure, with a
width smaller than a width of said ridge structure.

5

9. An optical semiconductor device as
10 claimed in claim 8, wherein said contact layer covers
a top surface and both side walls of said ridge
structure continuously.

15

10. An optical semiconductor device as
claimed in claim 9, wherein said first electrode
covers a top surface and both side walls of said
20 contact layer, corresponding respectively to said top
surface and both side walls of said ridge structure,
continuously.

25

11. An optical semiconductor device as
claimed in claim 10, wherein said ridge structure is
formed in a recess structure exposing said insulation
30 film, and wherein said first electrode fills said
recess structure.

35

12. An optical semiconductor device as
claimed in claim 10 wherein said third cladding layer

1 is formed of a nitride of a group III element.

5

13. An optical semiconductor device,
comprising:

a substrate of SiC having a first
conductivity type;

10 a first cladding layer having a first
conductivity type, said first cladding layer being
formed on said substrate epitaxially;

an active layer formed epitaxially on said
first cladding layer;

15 a second cladding layer having a second,
opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;

a third cladding layer having said second
conductivity type, said third cladding layer being
20 formed on said second cladding layer epitaxially;

a contact layer of said second conductivity
type, said contact layer being formed on said third
cladding layer;

25 a first electrode provided on said contact
layer;

a second electrode provided on said
substrate;

said third cladding layer forming a ridge
structure having a T-shaped cross-section,

30 said third cladding layer including, at a
bottom part thereof, a pair of cuts, such that said
cuts penetrate from respective lateral sides of said
ridge structure toward a center of said ridge
structure.

35

1 14. A method of fabricating a semiconductor
device, comprising the steps of:
 forming an insulation pattern on a
semiconductor layer such that said insulation pattern
5 has an opening; and
 forming, on said insulation pattern, a
regrowth region of a nitride of Al and a group III
element in correspondence to said opening,
 said step of forming the regrowth region
10 being conducted by an metal-organic vapor phase
epitaxy process.

15 15. A method as claimed in claim 14,
wherein said step of forming said regrowth region
includes the step of admixing a halogen to a source
material used in said metal-organic vapor phase
20 epitaxy process for forming said nitride.

25 16. A method as claimed in claim 15,
wherein said step of forming said regrowth region
includes the step of supplying said halogen to a
reaction chamber of a metal-organic vapor phase
deposition apparatus, in which said metal-organic
30 vapor phase epitaxy process occurs, separately to a
gaseous source of nitrogen.

35 17. A method as claimed in claim 14,
wherein said step of forming said regrowth region is

1 conducted by using a metal organic compound containing
halogen.

5

18. An optical semiconductor device,
comprising;

a substrate;

10 a first cladding layer of a nitride of a
group III element formed epitaxially on said
substrate, said first cladding layer having an n-type
conductivity;

15 a first optical waveguide layer of a nitride
of a group III element formed epitaxially on said
first cladding layer, said first optical waveguide
layer having an n-type conductivity;

20 an active layer of a nitride of a group III
element formed epitaxially on said first optical
waveguide layer;

an electron blocking layer of a nitride of a
group III element formed epitaxially on said active
layer, said electron blocking layer having a p-type
conductivity;

25 a second optical waveguide layer of a
nitride of a group III element formed epitaxially on
said electron blocking layer, said second optical
waveguide layer having a p-type conductivity;

30 a second cladding layer of a nitride of a
group III element formed epitaxially on said second
optical waveguide layer, said second cladding layer
having a p-type conductivity;

35 a contact layer of a nitride of a group III
element formed epitaxially on said second cladding
layer, said contact layer having a p-type
conductivity;

a first electrode provided on said contact

1 layer; and

a second electrode provided on said
substrate;

each of said electron blocking layer, said
5 second optical waveguide layer and said second
cladding layer being doped by Mg;

wherein said second optical waveguide layer
and said second cladding layer contain Mg therein with
a concentration level lower than a concentration level
10 of Mg in any of said electron blocking layer and said
contact layer.

15

19. An optical semiconductor device as
claimed in claim 18, wherein said second optical
waveguide layer and said second cladding layer contain
Mg with a concentration level not exceeding $4 \times$
20 10^{19}cm^{-3} .

25

20. An optical semiconductor device as
claimed in claim 19, wherein said electron blocking
layer and said contact layer contain Mg with a
concentration level exceeding $4 \times 10^{19} \text{cm}^{-3}$.

30

21. A semiconductor wafer, comprising:
an SiC substrate having an n-type
35 conductivity; and

an AlGaIn layer having an n-type conductivity
formed on said SiC substrate with a composition

1 represented as $\text{Al}_x\text{Ga}_{1-x}\text{N}$,
wherein said AlGa_N layer has a carrier
density in the range between $3 \times 10^{18} - 1 \times 10^{20} \text{cm}^{-3}$,
and
5 wherein said compositional parameter x is
larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

10

22. A semiconductor wafer as claimed in
claim 21, wherein said substrate contains carriers of
said first conductivity type with a concentration
15 level in the range from $1 \times 10^{18} - 1 \times 10^{20} \text{cm}^{-3}$.

20 23. A semiconductor wafer as claimed in
claim 21, wherein said compositional parameter x of
said buffer layer is less than 0.09 ($x < 0.09$).

25

24. An optical semiconductor device as
claimed in claim 21, wherein said substrate has a
(0001)Si surface of SiC and wherein said buffer layer
30 is formed on said (0001)Si surface in intimate contact
with said substrate.

35

1 ABSTRACT OF THE DISCLOSURE

 An optical semiconductor device includes an
SiC substrate having an n-type conductivity, and an
AlGa_N buffer layer having an n-type conductivity
5 formed on the SiC substrate with a composition
represented as Al_xGa_{1-x}N, wherein the AlGa_N buffer
layer has a carrier density in the range between 3×10^{18}
 $- 1 \times 10^{20} \text{ cm}^{-3}$, and the compositional parameter x
is larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

10

15


20

25

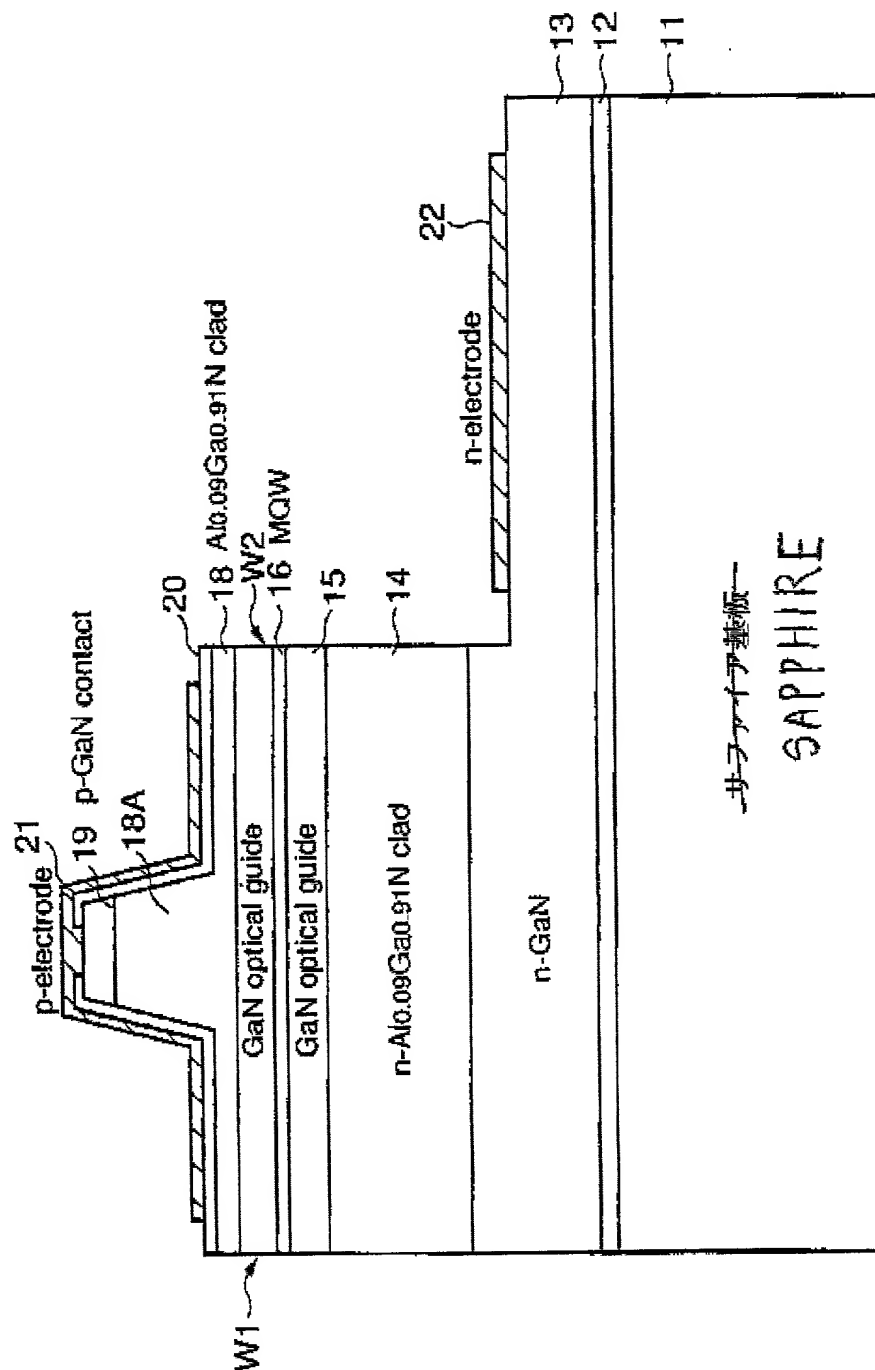
30

35

【書類名】 図面

【 1】

従来の青色レーザーダイオードの構成を示す図



【図2】

(A),(B)は、本発明の第1実施例の基礎となる実験で使われた試料、および実験結果を示す図

FIG 2A

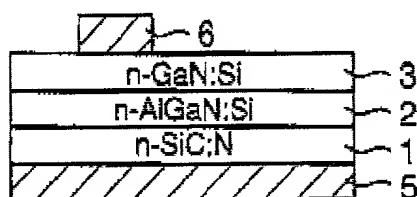
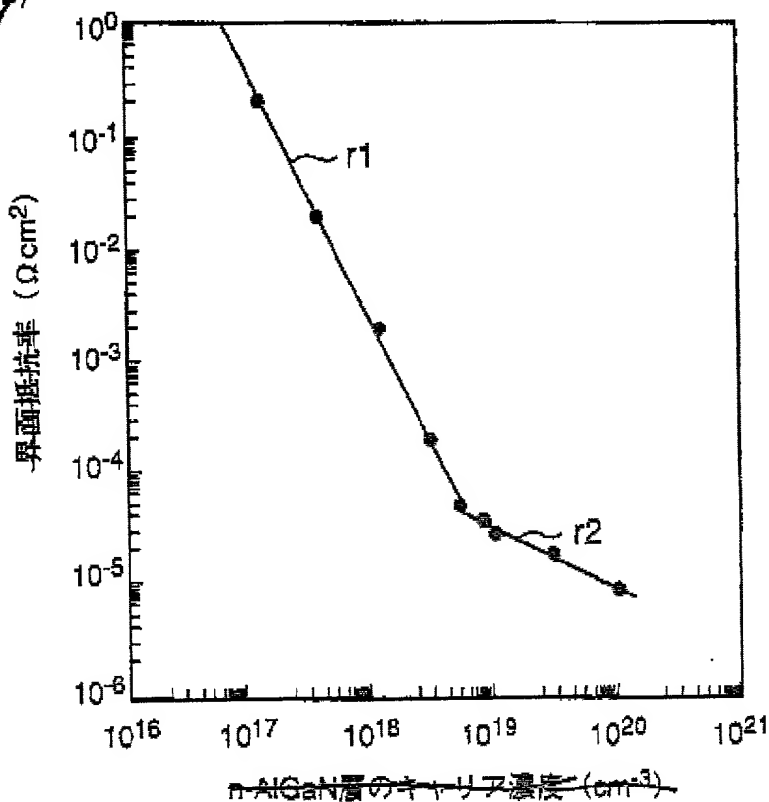


FIG 2B

INTERFACE RESISTIVITY

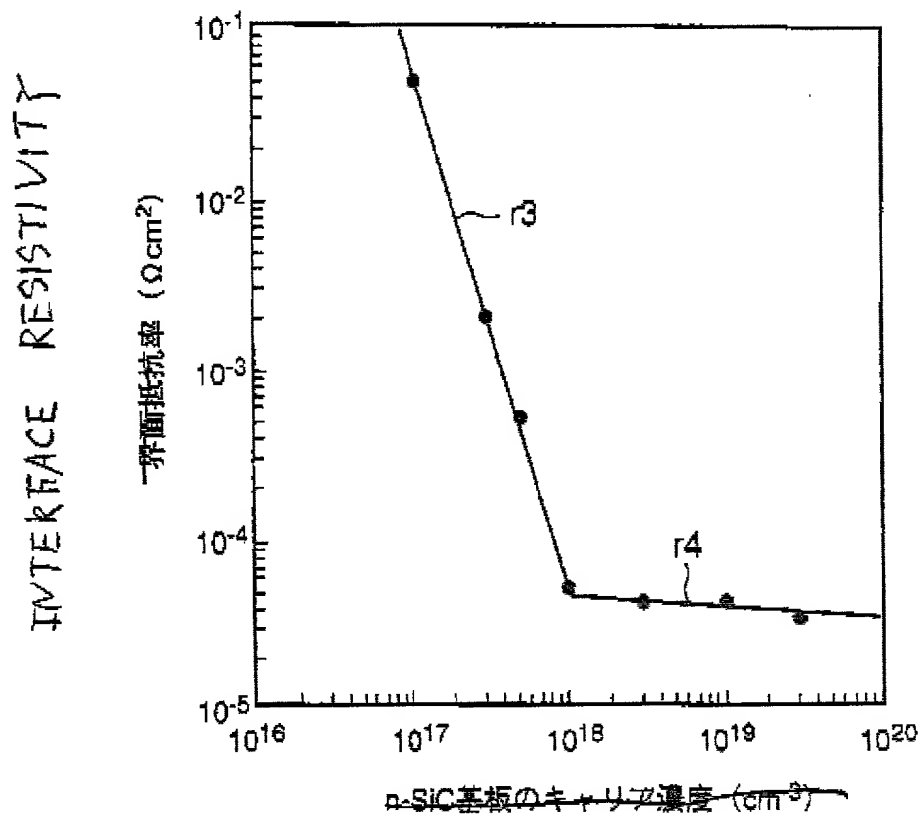


CARRIER DENSITY IN $n\text{-AlGaIn}$ (cm^{-3})

【図3】

FIG 3

本発明第1実施例の基礎となる実験の別の結果を示す図

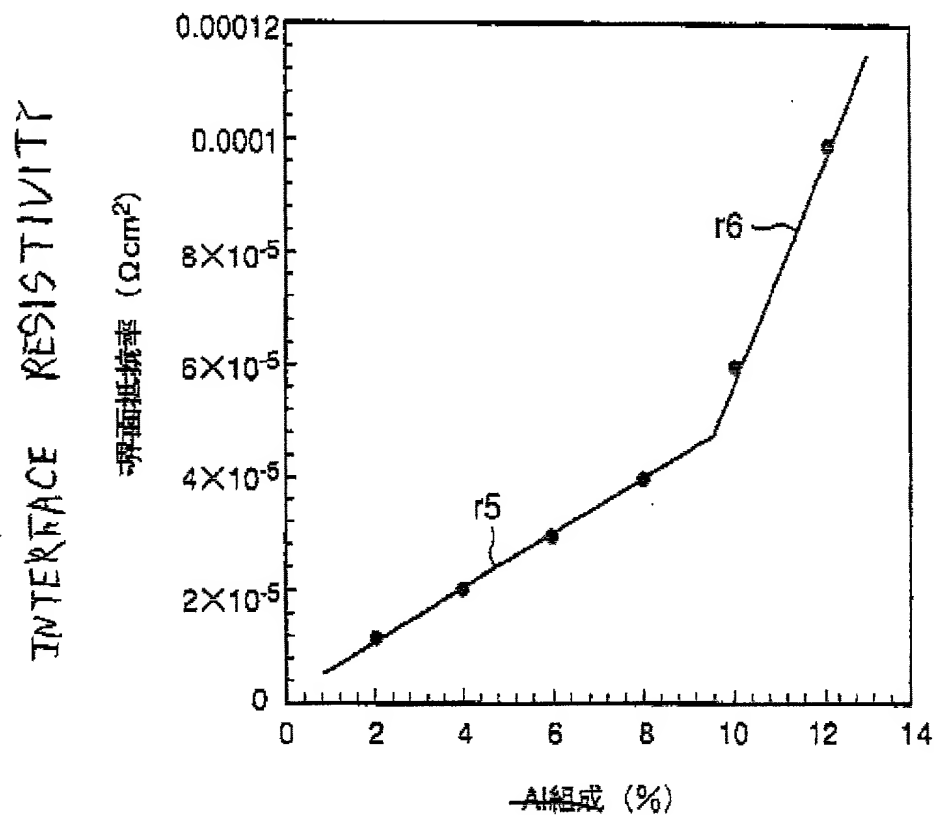


CARRIER DENSITY IN $n\text{-SiC}$ SUBSTRATE
(cm^{-3})

【図4】

FIG 4

本発明第1実施例の基礎となる実験の別の結果を示す図

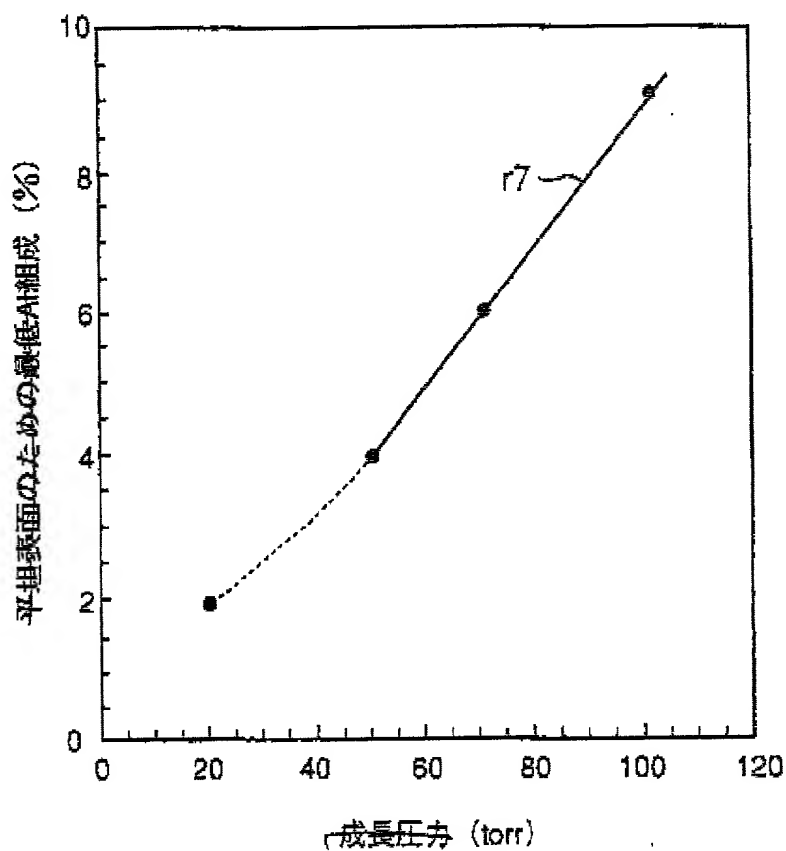


【図5】

FIG 5

MINIMUM AL CONTENT FOR PLANAR SURFACE

本発明第1実施例の基礎となる実験の別の結果を示す図



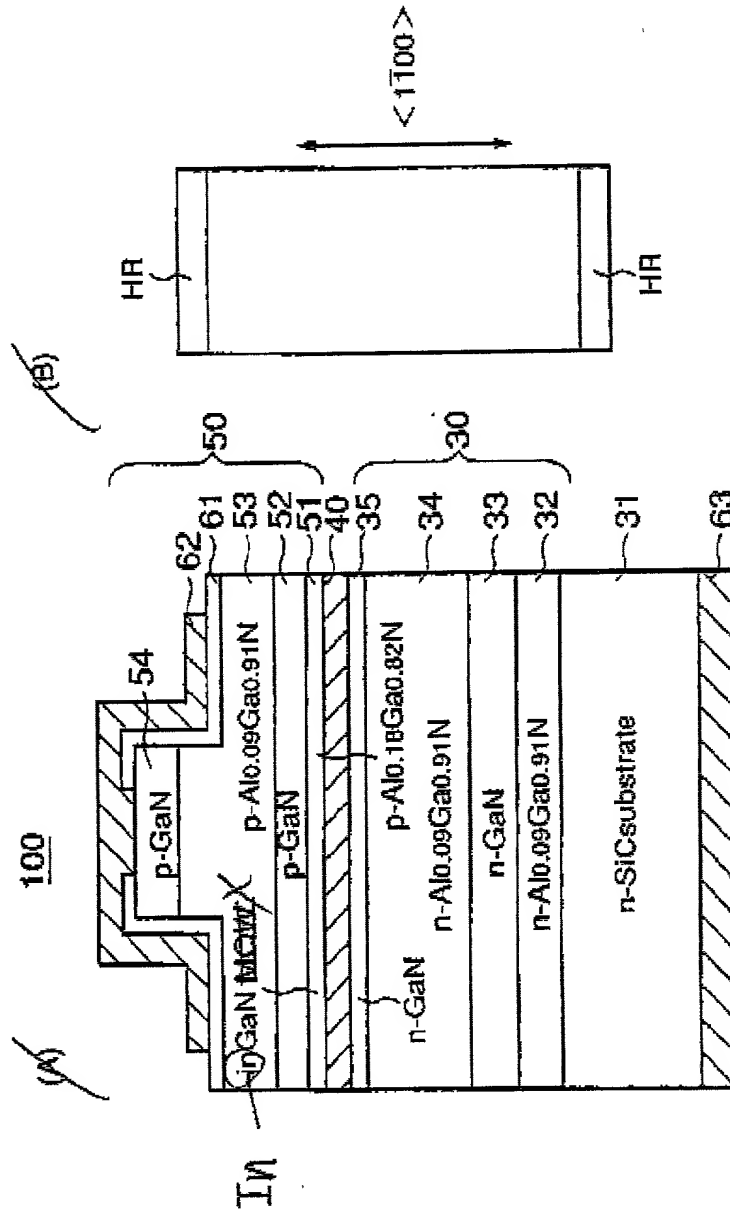
DEPOSITION PRESSURE

【図 6】

(A),(B)は、本発明の第1実施例によるレーザダイオードの構成を示す図

FIG 6B

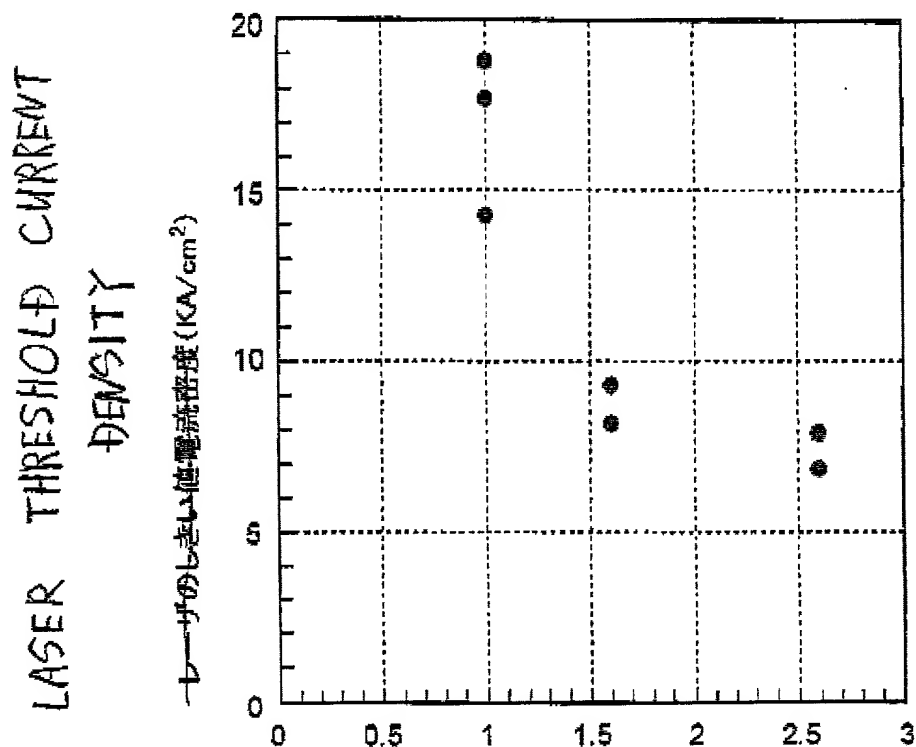
FIG 6A



【図7】

FIG 7

本発明の第2実施例の基礎となる実験の結果を示す図



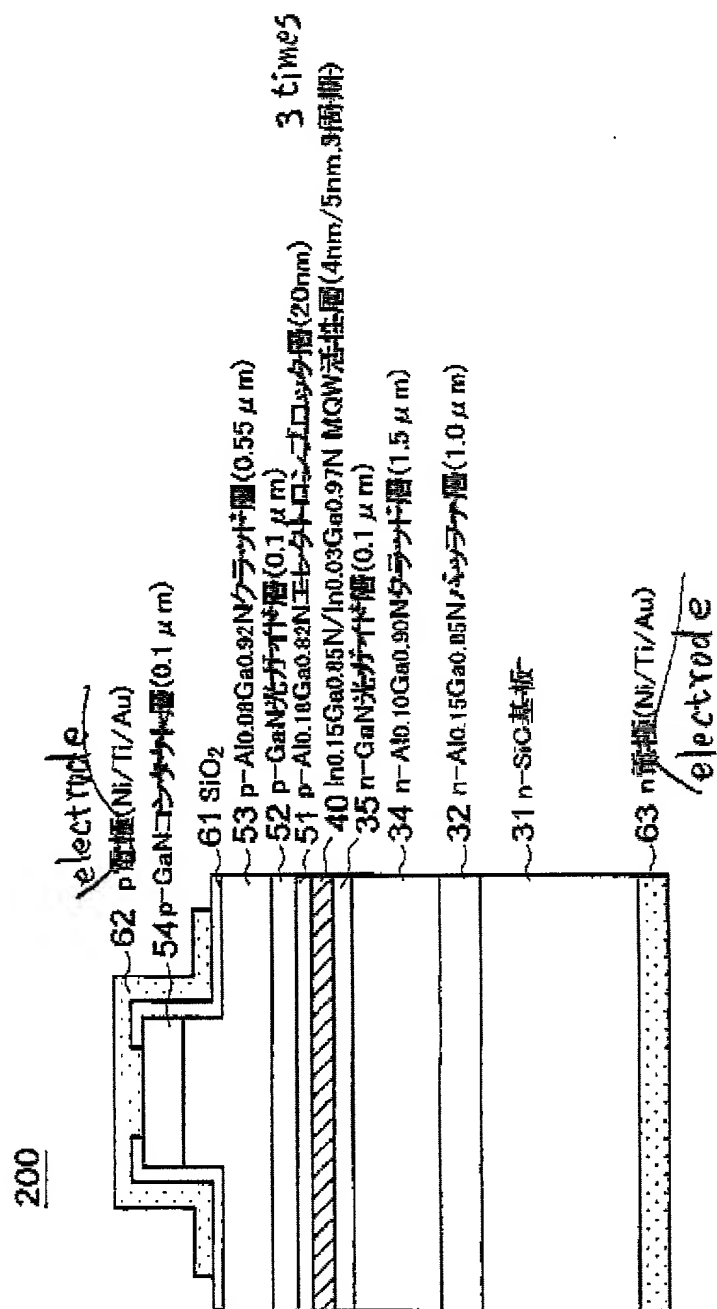
SiC基板と活性層の間に存在する層の膜厚の合計 (μm)

TOTAL FILM THICKNESS BETWEEN

SiC SUBSTRATE AND ACTIVE LAYER

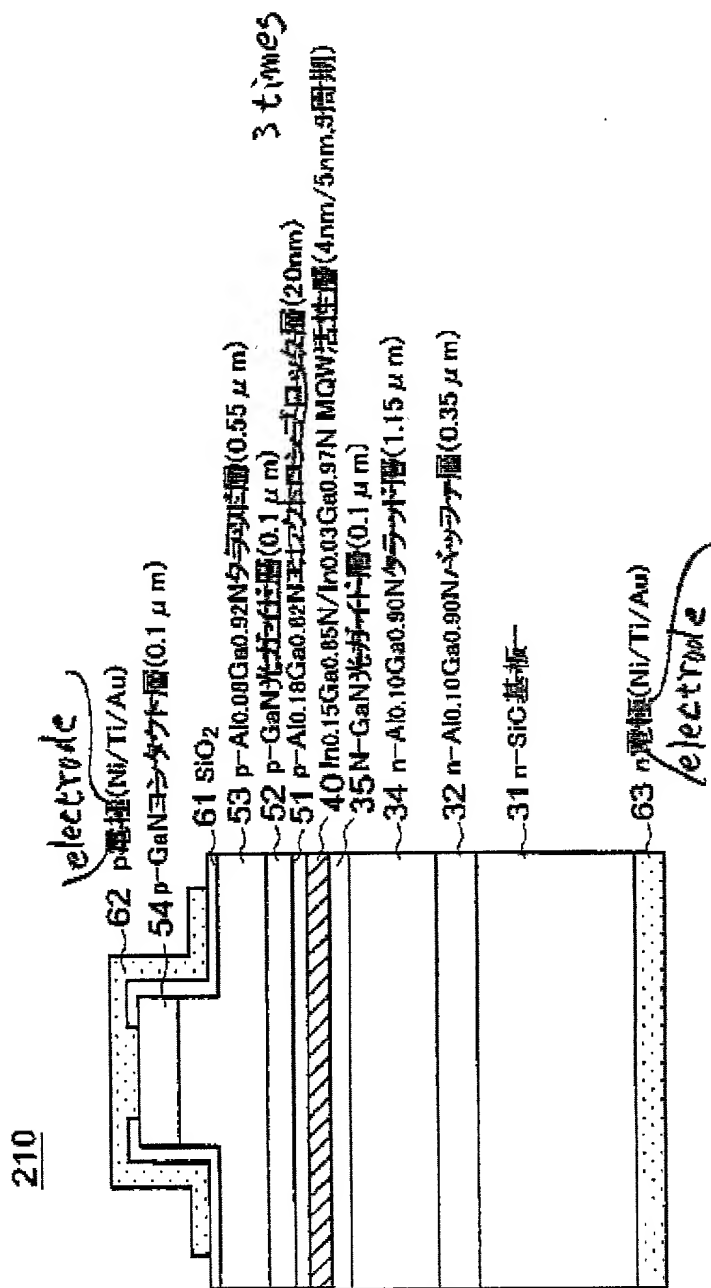
【図 8】

本発明の第2実施例によるレーザダイオードの構成を示す図



【図9】

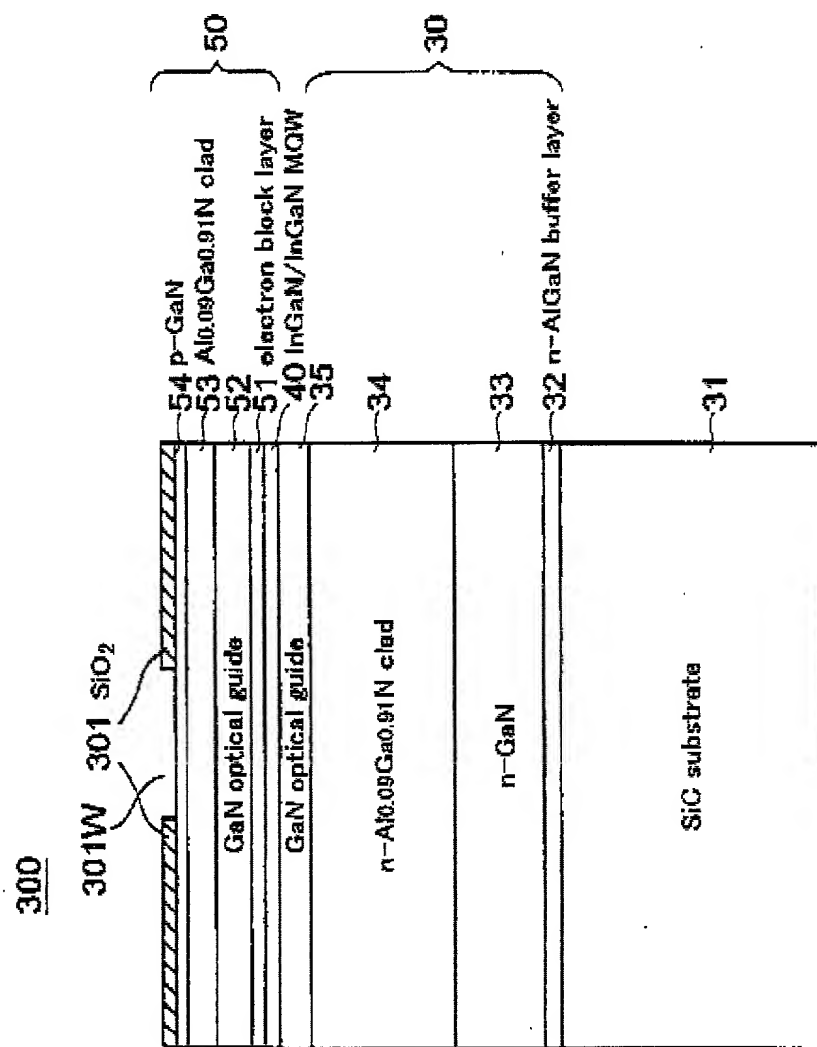
図8のレーザダイオードの一変形例を示す図



【図10】

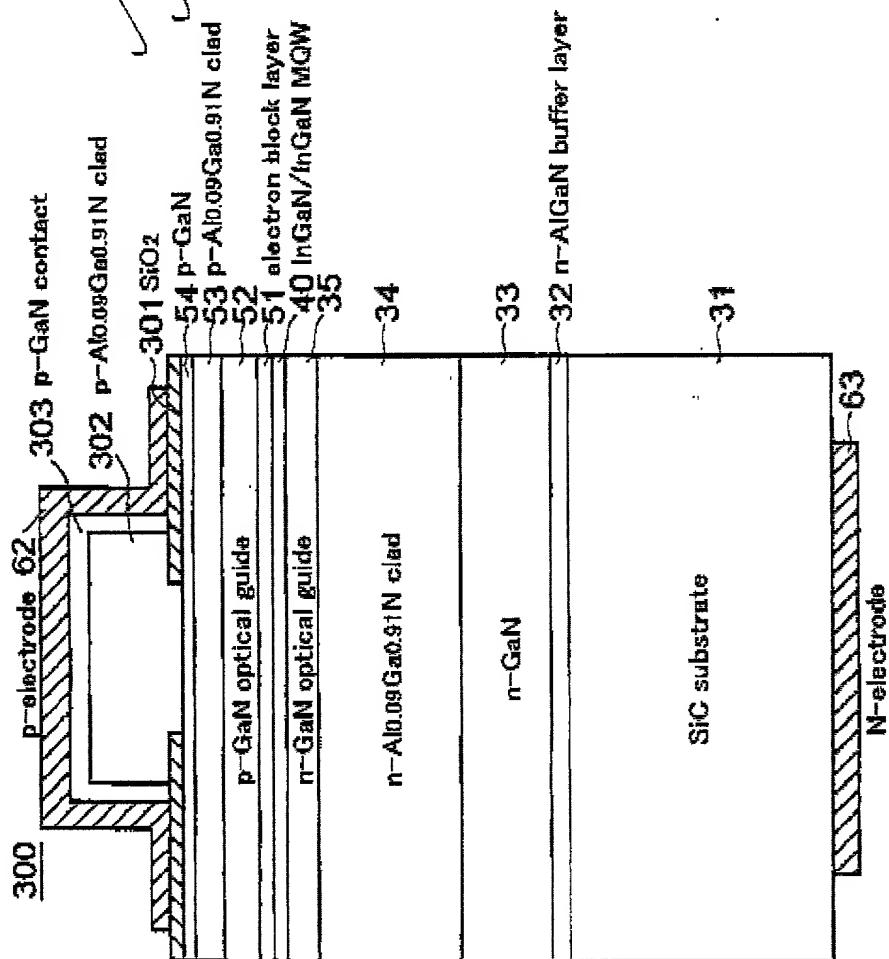
(A)は、本発明の第3実施例によるレーザダイオードの製造工程を示す図(その1)

FIG 10 A



【図11】

(B)は、本発明の第3実施例によるレーザダイオードの製造工程を示す図(その2)



(B)

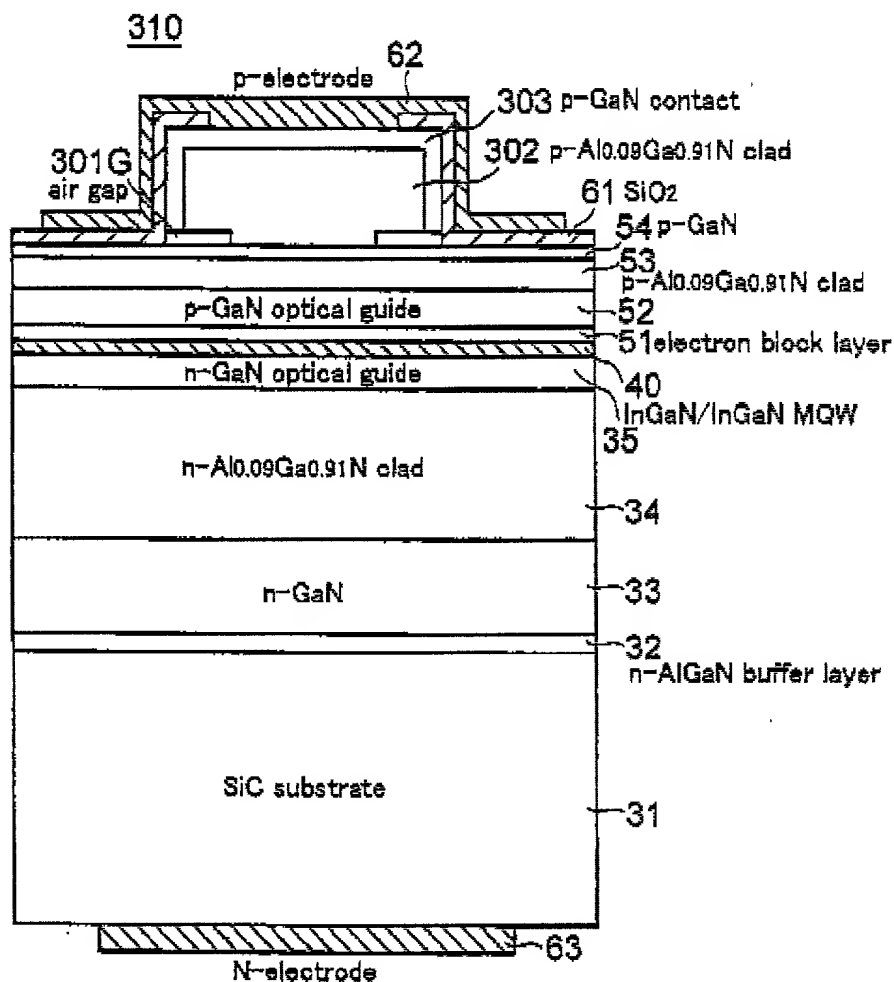
FIG. 10B

FIG. 10B

【図12】

FIG 11

本発明第3実施例によるレーザダイオードの一変形例を示す図



【図13】

(A)(B)は、本発明第3実施例の選択成長工程で使われるマスク、および本発明第4実施例の選択成長工程で使われるマスクを示す図

FIG 12A

(A)

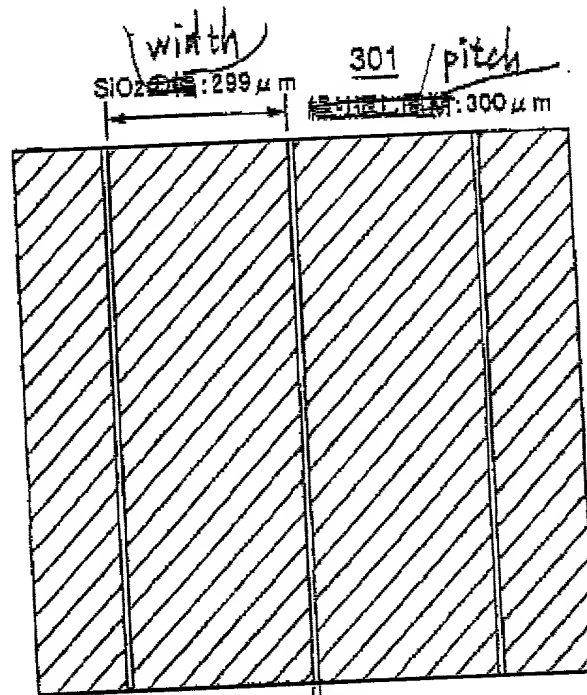
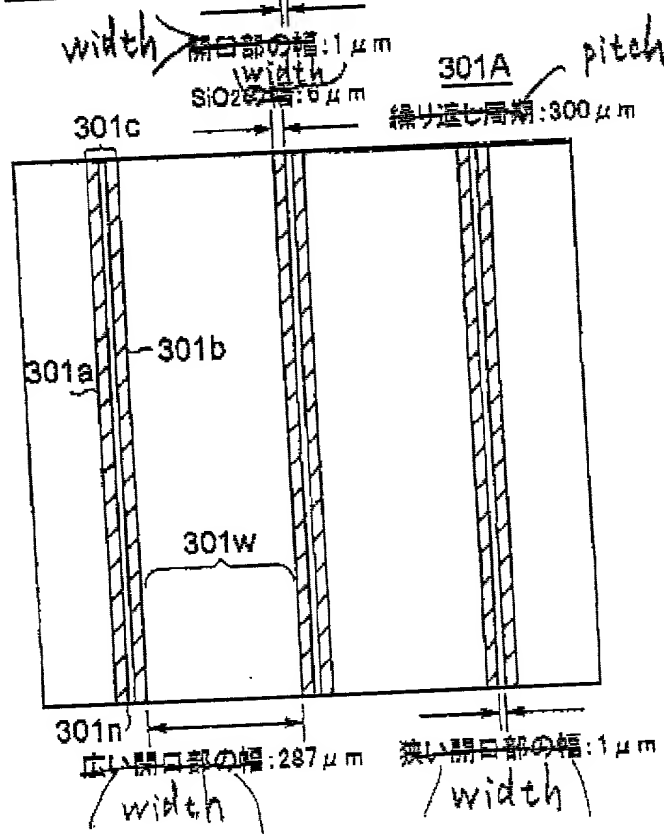


FIG 12B

(B)



【図 1 4】

本発明の第4実施例によるレーザダイオードの構成を示す図

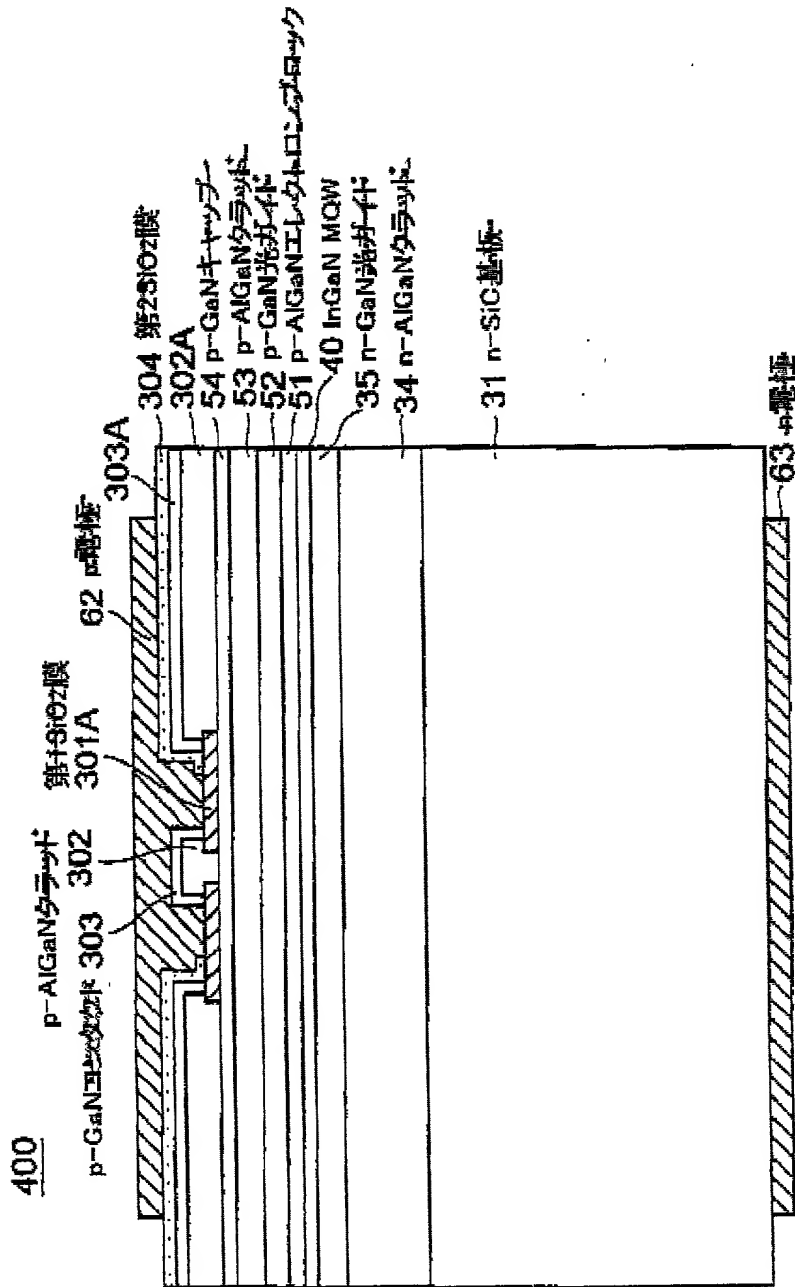
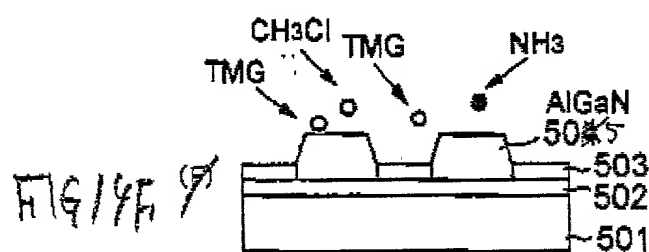
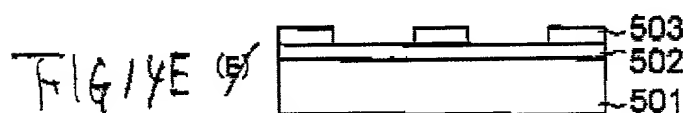
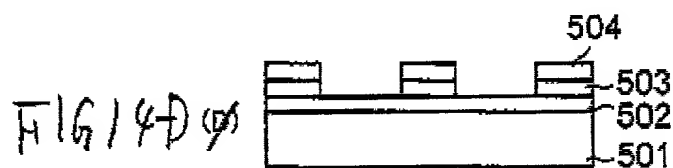
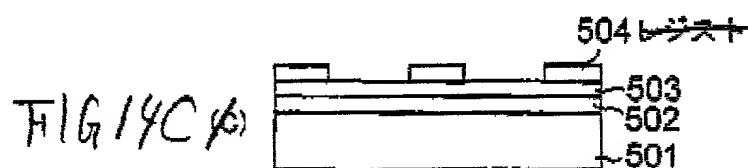
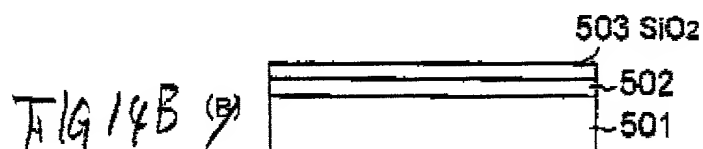
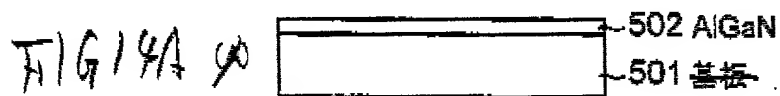


FIG 13

【図15】

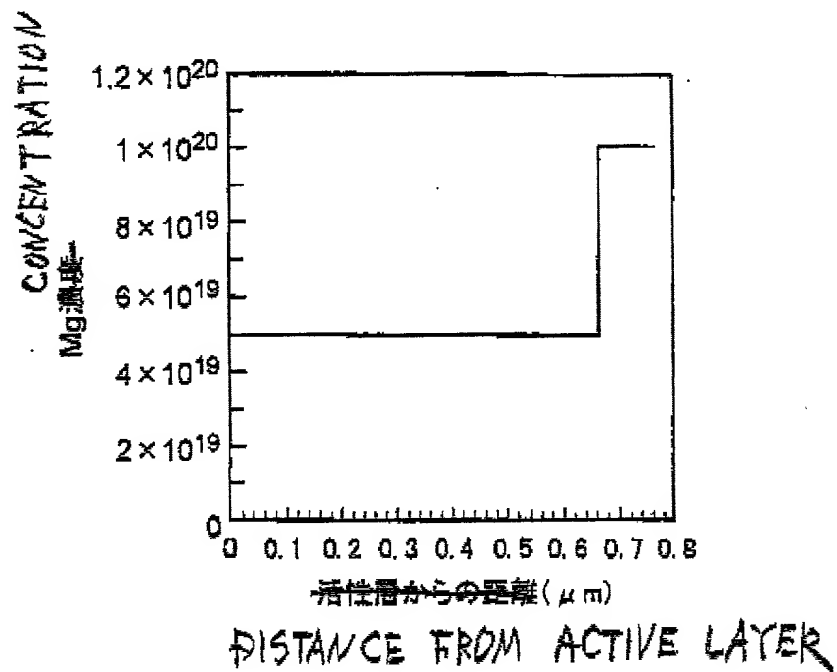
(A)~(F)は、本発明の第5実施例による選択成長工程を示す図



【図16】

FIG 15 PRIOR ART

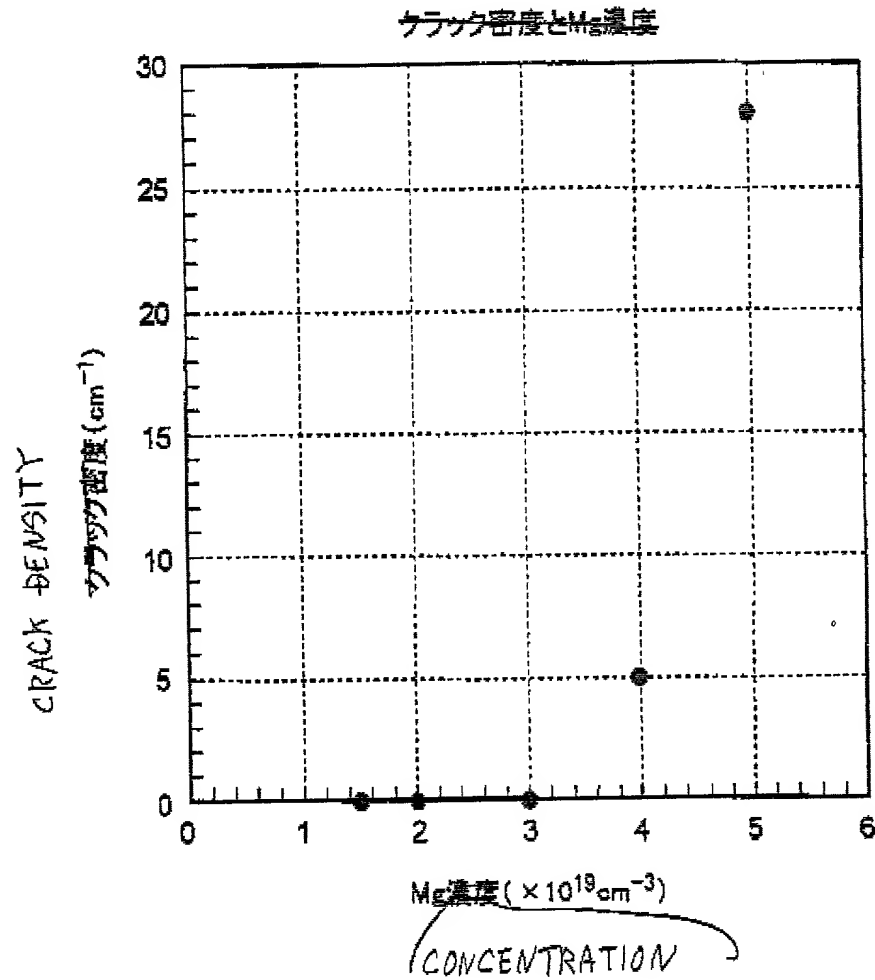
従来の青色レーザーダイオードにおけるp型エピタキシャル層中の不純物分布を示す図



【図17】

FIG 16

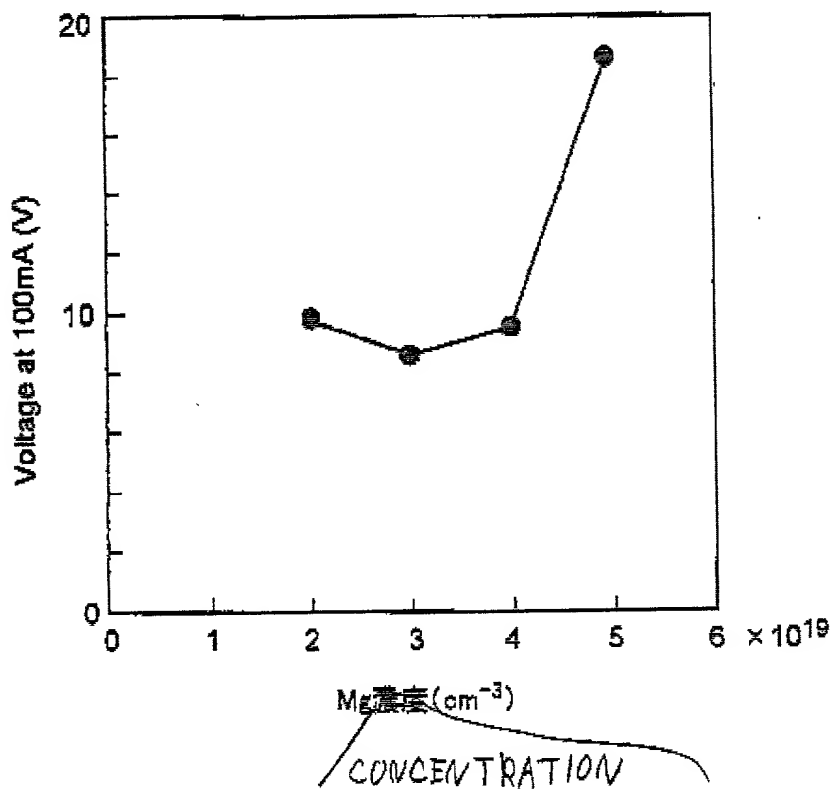
本発明の第6実施例の基礎となる実験結果を示す図



【図18】

FIG 17

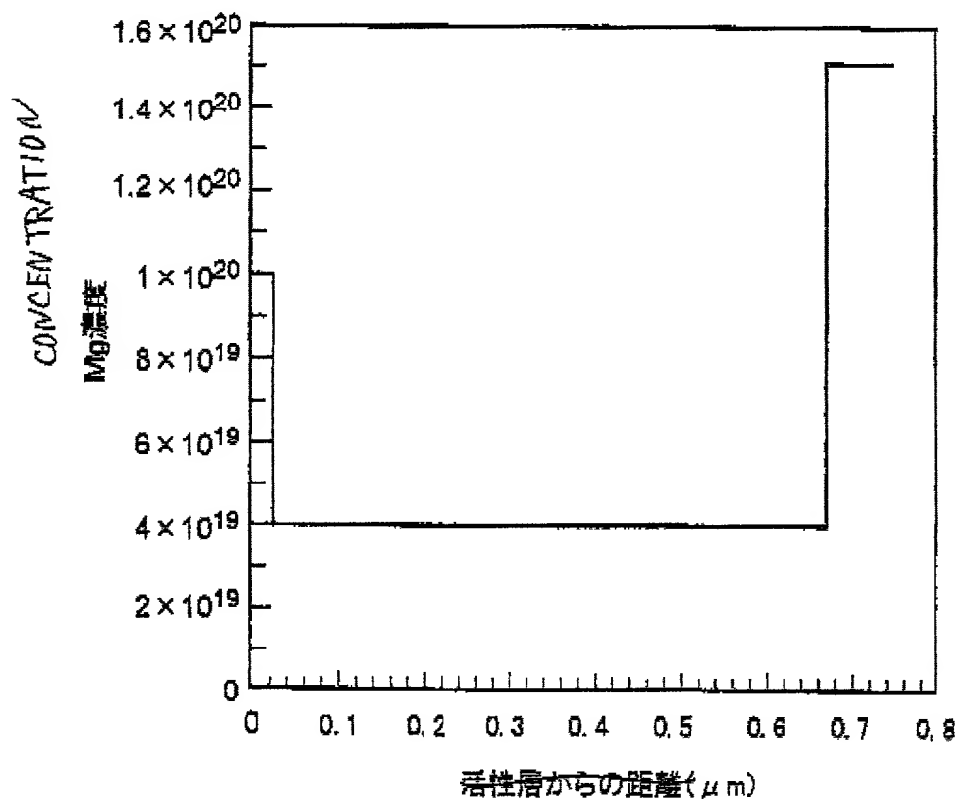
本発明第6実施例の基礎となる実験結果を示す別の図



【図19】

FIG 18

本発明の第6実施例によるレーザダイオードで使われる
不純物分布を示す図



DISTANCE FROM ACTIVE LAYER

【図20】

FIG/9

図19の一変形例による不純物分布を示す図

